

Hydro-BID: New Functionalities (Reservoir, Sediment and Groundwater Simulation Modules)

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**Water and Sanitation
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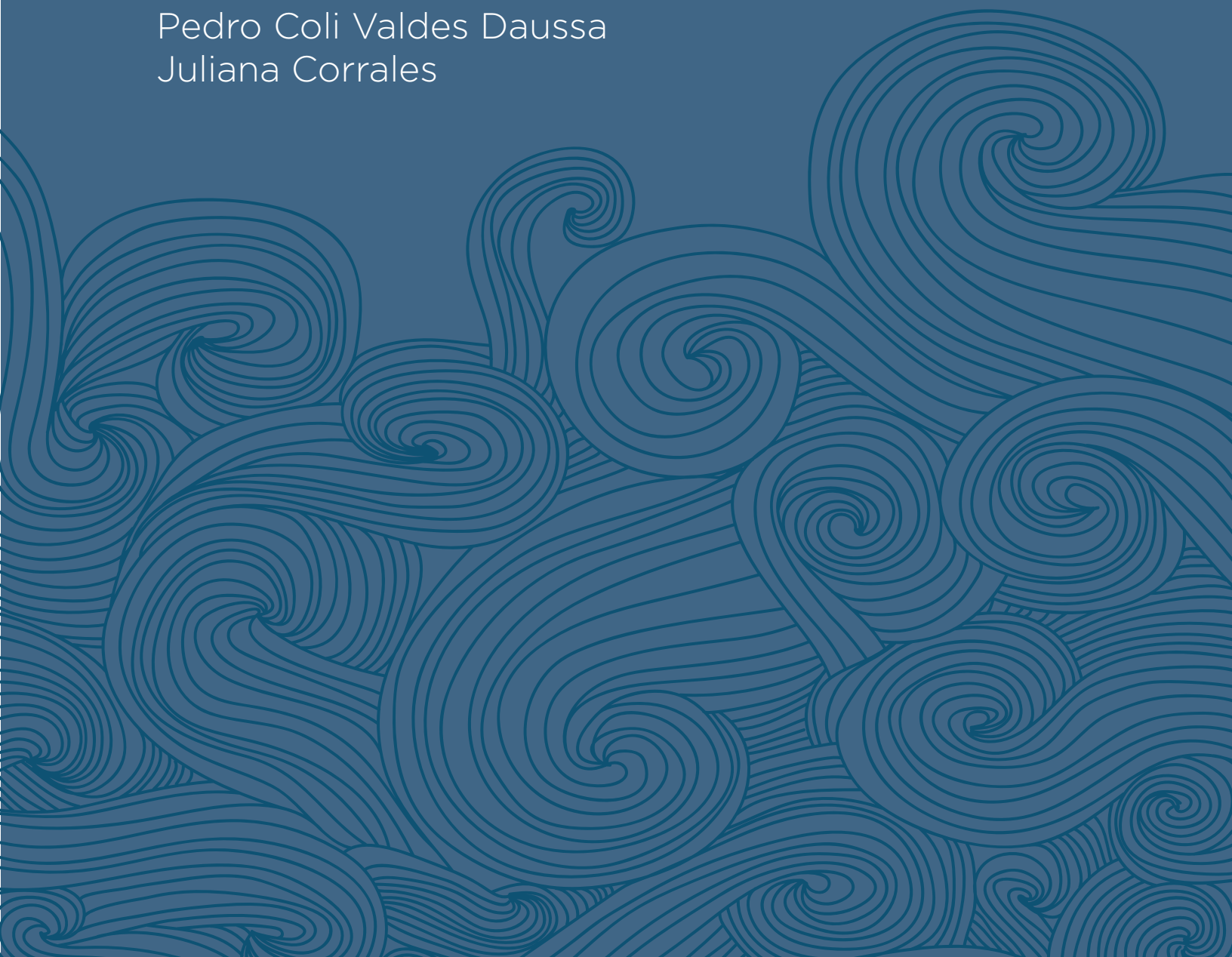
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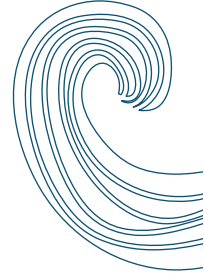
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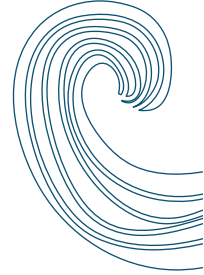
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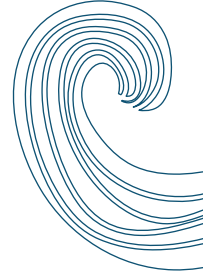


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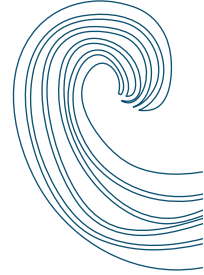
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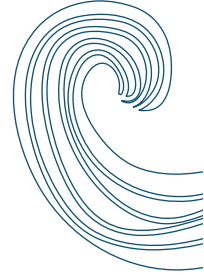
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Abbreviations and Acronyms

AHD	Analytical Hydrography Dataset
AWC	available soil water capacity
ET	evapotranspiration
GIS	geographic information system
GUI	graphical user interface
GWLF	Generalized Watershed Loading Factor
HSG	Hydrological Soil Groups
HWSD	Harmonized World Soil Database
IDB	Inter-American Development Bank
JRE	Java Runtime Environment
LAC	Latin America and the Caribbean
MUSLE	Modified Universal Soil Loss Equation
NHDPlus	U.S. National Hydrography Dataset
OVE	overall volume error
PET	potential evapotranspiration
PRMS	Precipitation-Runoff Modeling System
SCS	Soil Conservation Service
SLOP	Standard Linear Operating Procedure
SWAT	used Soil and Water Assessment Too
TN	Technical Note
USDA	U.S. Department of Agriculture
USGS	United States Geological Survey
USLE	Universal Soil Loss Equation
WaterFALL®	Watershed Flow and ALLocation model



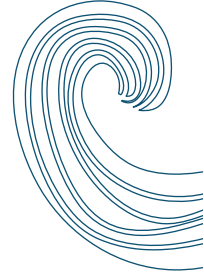
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Development of Hydro-BID has benefitted from previous work performed with our colleagues at RTI on the proprietary Watershed Flow and ALlocation (WaterFALL®) system. We wish to acknowledge the contributions of Michele Eddy and James Rineer in developing WaterFALL; Aaron Parks, Matthew Scruggs, and Adam Shelton for programming support on Hydro-BID; Jimmy Bisese for programming the AHD navigation tool; and Brandon Bergenroth and John Buckley for indexing the land use, soil, and climate data for Hydro-BID applications and testing. Jessi Allen has contributed in evaluating and testing the new modules.

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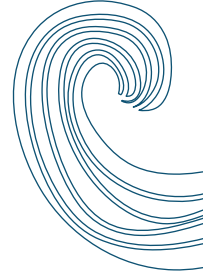
Foreword

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

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

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

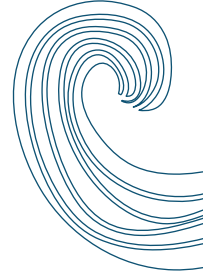
In Phase I of this effort, RTI prepared a working version of Hydro-BID that includes: (1) the Analytical Hydrography Dataset for Latin America and the Caribbean (LAC AHD), a digital representation of 229,300 catchments in Central America, South America, and the Caribbean with their corresponding topography, river, and stream segments; (2) a geographic information system (GIS)-based navigation tool to browse AHD catchments and streams with the capability of navigating upstream and downstream; (3) a user interface for specifying the area and period to be modeled and the period and location for which water availability will be simulated; (4) a climate data interface to obtain rainfall and temperature inputs for the area and period of interest; (5) a rainfall-runoff model



based on the Generalized Watershed Loading Factor (GWLF) formulation; and (6) a routing scheme for quantifying time of travel and cumulative flow estimates across downstream catchments. Hydro-BID generates output in the form of daily time series of flow estimates for the selected location and period. The output can be summarized as a monthly time series at the user's discretion.

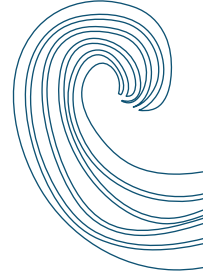
In Phase II of this effort, RTI has prepared an updated version of Hydro-BID that includes (1) improvements to the user interface; (2) a module to simulate the effect of reservoirs on downstream flows; (3) a module to link Hydro-BID and groundwater models developed with MODFLOW and incorporate water exchanges between groundwater and surface water compartments into the simulation of surface water availability; and (4) an application for modeling sediment loads using Modified Universal Soil Loss Equations and Gavrilovic Equation at specified locations in a surface water network, with precomputed parameters including soil erodibility factor and topographic factor, with user inputs of cover management and support practice factors based on land use.

RTI has performed case study analyses using Hydro-BID in partnership with IDB water-sector client institutions in several countries. This Technical Note (TN3) provides an overview of Hydro-BID new modules and user guides to their implementation. The following table provides description of the Hydro-BID Technical Note series.



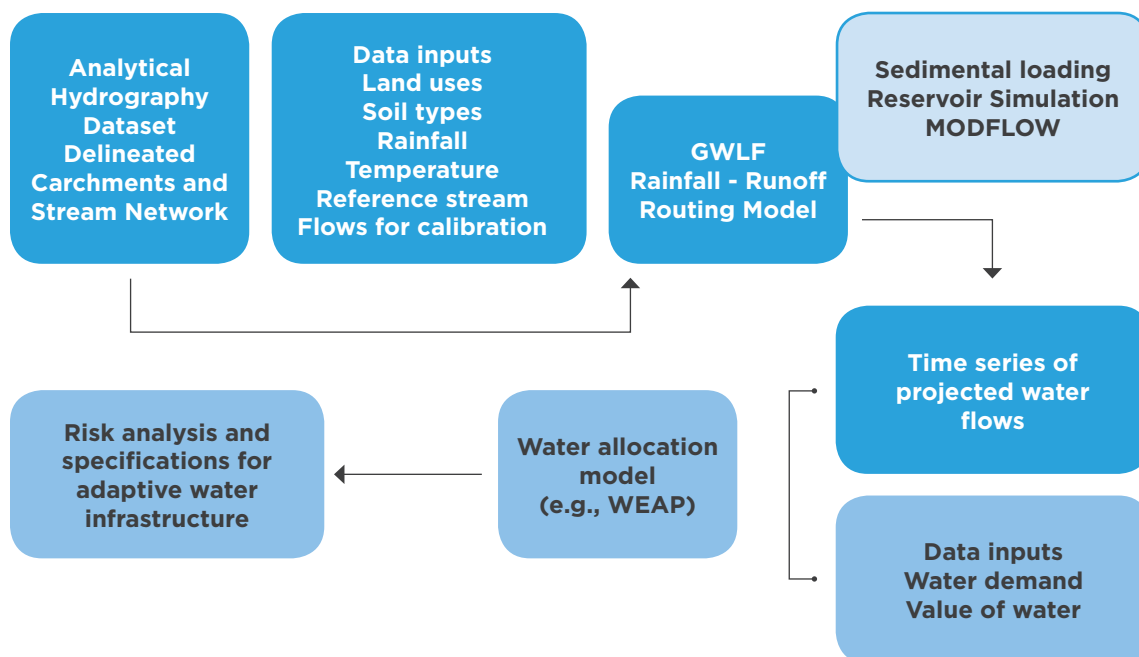
Technical Notes in the Hydro-BID Series ¹		
No.	Title	Summary
TN 1	An Analytical Hydrography Dataset for Latin America and the Caribbean	TN1 provides an overview of the LAC AHD, a geospatial dataset providing a digital representation of over 229,000 catchments in Central America, South America, and the Caribbean. The LAC AHD is patterned after NHDPlus and serves as the “base layer” for the Hydro-BID modeling system.
TN 2	Hydro-BID: An Integrated System for Modeling Impacts of Climate Change on Water Resources	TN2 provides an overview of the Hydro-BID modeling system, including the LAC 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. Basin models developed using Hydro-BID provides time series of simulated stream flows based on user inputs.
TN 3	Hydro-BID: New Functionalities (Reservoir, Sediment and Groundwater Simulation Modules)	TN3 provides an overview of new modules and additional enhancement included in the new version of Hydro-BID like reservoir simulation, sediment load simulation, and interaction between surface and groundwater modeling. The graphical user interface (GUI) of Hydro-BID is greatly enhanced to facilitate model set-up and model calibration, and provides additional graphical plots to evaluate model performance. Output from the model also includes a summary of catchment-scale water balance components that can be mapped.

¹ For the complete list and downloads of Hydro-BID Technical Notes please visit <http://www.iadb.org/en/sector/water-and-sanitation/overview,18357.html>

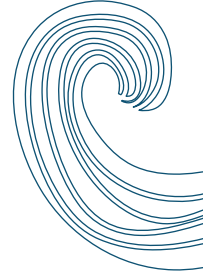


The Hydro-BID system has three major components: the Analytical Hydrographic Dataset (AHD), the database, and the hydrology model. Figure 1-1 presents a schematic representation of the integrated Hydro-BID system for quantitative simulation of hydrology and climate change. The system is built on an AHD for the Latin American and Caribbean (LAC) region. The AHD is described in detail in Technical Note 1 of this series. The AHD utilizes the data structure and the catchment and stream network topologies of the AHD. The database incorporates the AHD catchments and its properties such as drainage area, stream length, slope, land uses, soil types, rainfall, and temperature within the study area. The current version database is organized in SQLITE. The hydrology model—referred to as Hydro-BID—is based on an enhanced Generalized Watershed Loading Function (GWLF) model, coupled with a novel lag-routing methodology developed by RTI and that is described in detail in Technical Note 2. Hydro-BID also includ

Figure 1-1. Hydro-BID Flow Chart



In the current version of Hydro-BID, additional modules are implemented. These modules work seamlessly with the original rainfall-runoff model once the modules are selected to be included in the simulation. The three modules are 1) reservoir simulation, 2) sediment transport and 3) surface and groundwater interaction using MODFLOW. While the first two modules are integrated within the Hydro-BID model, the surface water and groundwater interaction module requires an external groundwater model, MODFLOW. The link between Hydro-BID and MODFLOW is achieved through running the two models sequentially and sharing input/output data files.



In addition to the new modules, the graphical user interface (GUI) of Hydro-BID is greatly enhanced. The enhancement includes grouping tasks into tabs of model setup, calibration parameter savings, and special tools, as well as extensive graphical viewing of outputs. We have added more graphical and statistical output displays to enable calibration and validation of model simulations.

Model output is generated as a time series of projected water flows, at either a daily or monthly scale. The system has a GUI to accept model input, as well as to display graphical and tabular summary outputs.

Hydro-BID has been developed to serve as a key planning tool for:

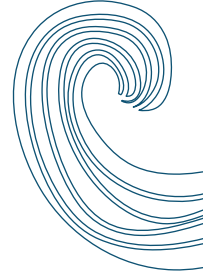
- water resources planning and management agencies;
- drainage/flood control authorities;
- irrigation authorities;
- hydroelectric power generators;
- water supply and sanitation utilities; and
- industrial water users.

1.1 Organization of the Technical Note

Following this introduction, Chapter 2 describes the foundation of Hydro-BID new modules by providing information regarding governing equations and parameter estimations. Chapter 3 presents method of data organization in Hydro-BID. Chapter 4 presents a user's guide for Hydro-BID by first showing a succinct version of the installation and running the model and later describing the detailed step-by step function of the model.

2. Hydro-BID System Functionality





This chapter describes the basic equations governing the reservoir simulation, sediment loading functions and surface water and groundwater interaction; and the data and parameter requirements. Information regarding the Generalized Watershed Loading Function (GWLF), the RTI lag routing methodology and the general data and parameters requirements can be found on Technical Note 2.

2.1.1 Sediment Loading

In this new version of Hydro-BID, two methodologies were implemented to determine the sediment loads from catchments. The first method is based on the Modified Universal Soil Loss Equation (MUSLE) and the second is based on Garrilovic equation (1959) modified by Zemlijc (1971). Both methods are seamlessly linked to the GWLF simulation. While MUSLE is implemented to generate daily sediment loads for catchments, the Garrilovic method is developed only for annual sediment loads. The following sections describe the two methodologies and their parameters.

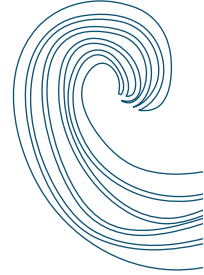
2.1.1 Modified Universal Soil Loss Equation

The commonly used sediment transport loading equations are based on annual total sediment loads from watersheds. By employing these equations in conjunction with Hydro-BID on a daily time step, we focus on developing a dynamic sediment load function that represents the prevailing daily and seasonal weather conditions. In addition, the sediment loads calculated are inherently dependent on the different land uses in a watershed. As Hydro-BID is designed to generate daily runoff from each land use separately in a watershed (i.e., catchment), daily calculated land use-specific runoff was used to generate corresponding sediment loads, which can be summed to a total load for watershed. The sediment loads are also subject to the RTI hydrologic lag-routing scheme described in Technical Note 2.

Erosion caused by rainfall is computed with MUSLE (Williams, 1975), and implemented closely following the MUSLE implementation in the widely used Soil and Water Assessment Tool (SWAT) (Neitsch et al., 2009). MUSLE is a modification of the original USLE, which computes average annual erosion. MUSLE computes daily rates of erosion as a function of daily runoff and the USLE parameters, while USLE predicts gross annual erosion as a function of rainfall energy. For MUSLE, the rainfall energy is represented by using peak flow in addition to the surface runoff. The daily variables required to compute the daily rate of sedimentation are provided by the hydrology component.

From Williams (1975):

$$Sed_t = 11.8(Q_t Q_{peak})^{0.56} K_{USLE} C_{USLE} P_{USLE} LS_{USLE} CFRG \quad (E.1)$$



where Sed_t is the sediment yield on day t (metric ton, i.e., tonnes)

Q_t is the surface runoff volume for that day (m^3), this is a daily output of the hydrology model

Q_{peak} is the peak daily flow (m^3/s), calculated as described below

LS_{USLE} is the topographic factor, calculated as described below

K_{USLE} is the soil erodibility factor, which is user input

C_{USLE} is the cover management factor, which is user input

P_{USLE} is the support practice factor, which is user input

CFRG is the coarse fragment factor, which is user input.

Internally calculated MUSLE parameters are discussed below.

Q_{peak} is the peak flow for day t and is computed using the modified rational formula:

$$Q_{peak} = \frac{\alpha_{tc} Q_t Area}{3.6 t_{con}} \quad (E.2)$$

where Area is surface area of interest (km^2)

t_{con} is the time of concentration (hr)

3.6 is a unit conversion factor

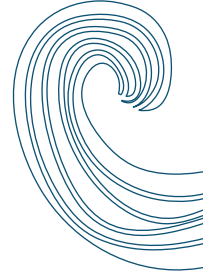
α_{tc} is the fraction of rain falling during t_{con} , calculated using E.21:

$$\alpha_{tc} = 1 - \exp[2t_{con} \ln(1 - \alpha_{0.5})] \quad (E.3)$$

where $\alpha_{0.5}$ is the fraction of daily rainfall falling in the half-hour of highest intensity. Calculating $\alpha_{0.5}$ requires a number of historical data analyses to generate minimum, mean, and maximum monthly half-hour rainfalls. In addition, the randomness of the half-hour fraction rainfall computation can produce values that are not consistent in time. Therefore, the approach we have adopted that will also require less data is the following:

- From daily rainfall data for each day compute the **maximum** allowable fraction, $\alpha_{0.5u}$, as E.4.

$$\alpha_{0.5u} = 1 - \exp\left(\frac{-125}{R_{day} + 5}\right) \quad (E.4)$$



where R_{day} is the rainfall depth (mm) for the day.

- Per SWAT documentation, always assume the **minimum** allowable $a_{0.5min}$ is 0.02083.
- If $a_{0.5u}$ is lower than or equal to $a_{0.5min}$ use $a_{0.5} = a_{0.5u}$.
- If $a_{0.5u}$ exceeds $a_{0.5min}$ then use $a_{0.5} = (2a_{0.5u} + a_{0.5min})/3$.

Time of concentration, t^{con} is the time required for flow to come to the outlet from the longest stream segment in the catchment. There are several empirical formulas developed for different land use types. We applied the Soil Conservation Service (SCS) Lag Formula, E.5. The SCS equation for estimating watershed lag calculates the travel time in hours from the center of mass of the excess rainfall to the time of the peak discharge.

$$T_c = \frac{L^{0.8} \left(\frac{1000}{CN} - 9 \right)^{0.7}}{1140S^{0.5}} \quad (E.5)$$

Where T_c is the time of concentration (hr)

L is the flow length (ft)

CN is the curve number

S is the average slope (%)

L is the flow length, which can be calculated using the following equation by Mockus (USDA, 1972):

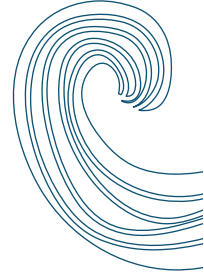
$$L = 209A^{0.6} \quad (E.6)$$

Where L is the flow length (ft)

A is the drainage area (acres)

The main approach to compute sediment loads using Hydro-BID follows these five steps:

1. For each land use type, we calculate runoff and peak flow
2. For each land use type, we calculate sediment load using MUSLE using the area of the land use
3. Add all the sediments from the land uses and obtain sediment load for the catchment (metric tonnes/day)



4. Perform routing for all catchments upstream of a given catchment and add all sediment loadings (metric tonnes/day)
5. Calculate sediment concentration after routing by dividing the total sediment load (local plus routed) (tonnes) by outflow from the catchment

The outputs from the model are the total sediment loads (tonnes/day) and sediment concentration (mg/L). The sediment concentration at the outlet of each catchment is calculated by dividing the routed flow by routed sediment:

$$SedCON_t = \frac{F_t}{Sed_t} * Unit_conversion_factor \quad (E.7)$$

Where $SedCON_t$ is sediment concentration (mg/L), F_t is total flow (m^3/s), and Sed_t (tonnes/day), and unit conversion factor = 10^6

2.1.2 MUSLE Sediment Parameters

In this section the parameters used in MUSLE are listed and also, an attempt to estimate initial parameters is described. **Table 2-1** presents the MUSLE variables and parameters and sources of the initial estimates of parameters.

Cover Management Factor, C_{USLE} and Support Practice Factor, P_{USLE}

The Cover and Practice Management Factors presented in **Table 2-2** for USLE are based on land use classification assignments used in US EPA Exposure assessment models, 3MRA (US EPA, 2003).

Table 2-1. Sediment Variables and Parameters

Variables	Description	Sources
Sediment[day]	Sediments (tonnes/day)	Calculated
Area	Area of individual land use (ha)	landUseArea
Runoff[day]	Runoff from the land use (cm)	landUseRunoff (calculated using GWLF)
K_{USLE}	Soil erodibility factor	Estimated from soil properties
C_{USLE}	Cover Management factor	Assigned using land cover and practice management factors for USLE
P_{USLE}	Support practice factor	Assigned using cover and practice management factors for USLE
LS_{USLE}	Topographic factor	Estimated from catchment characteristics
CFRG	Coarse and fragmentation factor	Assumed = 1

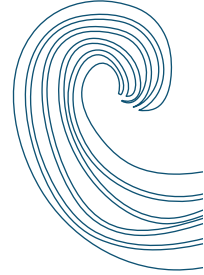


Table 2-2. Initial Estimate of Cover Management Factor (CUSLE), and Support Practice Factor (P)

LU01_ID	C_Factor	P_Factor
10	0	1
21	0.01	1
22	0.01	1
23	0.01	1
24	0.01	1
31	1	1
32	1	1
40	0.005	1
50	0.01	1
70	0.01	1
81	0.01	1
82	0.08	0.5
90	0	1
95	0	1

Soil Erodibility Factor, K_{USLE}

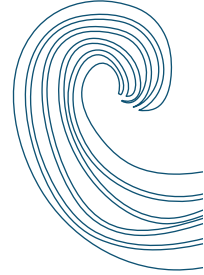
Soil erodibility is estimated based on FAO soil textures. To compute the erodibility, four soil characteristics are required: percent sand (m_s), percent clay (m_c), percent silt (m_{silt}), and percent organic matter (orgC). These characteristics are given in **Tables 2-3 and 2-4**. The empirical equation used to estimate K_{USLE} (Williams, 1995) is:

$$K_{USLE} = f_{csand} * f_{c-si} * f_{orgc} * f_{hissand} \quad (E.8)$$

Where,

$$f_{csand} = \left(.2 + .3 \exp \left(-0.256 * m_s * \left(1 - \frac{m_{silt}}{100} \right) \right) \right) \quad (E.9)$$

$$f_{c-si} = \left(\frac{m_{silt}}{m_c + m_{silt}} \right)^{0.3} \quad (E.10)$$



$$f_{orgc} = \left(1 - \frac{0.0256 * orgC}{orgC + \exp\left(-5.51 + 2.29 * \left(1 - \frac{m_s}{100}\right)\right)} \right) \quad (E.11)$$

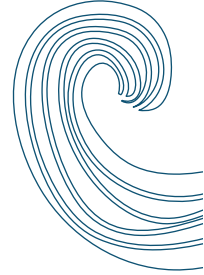
$$f_{hissand} = \left(1 - \frac{0.7 * \left(1 - \frac{m_s}{100}\right)}{\left(1 - \frac{m_s}{100}\right) + \exp\left(-5.51 + 2.29 * \left(1 - \frac{m_s}{100}\right)\right)} \right) \quad (E.12)$$

Table 2-3. FAO Texture of Soils

FAO-Texture	% Clay (m_c)	% Sand (m_s)	% Silt (m_{silt})
C - Clay	50	30	20
CL - Clay Loam	34	33	33
L - Loam	18	42	40
LS - Loam Sand	6	82	12
Sa - Sand	5	92	3
SC - Sand Clay	42	52	6
SCL - Sandy Clay Loam	28	60	12
SL - Sandy Loam	10	65	25
Si - Silt	6	7	87
SiC - Silty Clay	47	7	46
SiCL - Silty Clay Loam	34	10	56
SiL - Silty Loam	20	20	60

Table 2-4. FAO Organic Material Data

FAO-OM Code	Organic Carbon ($orgC$)	
	Percent WSeight	Used in Hydro-BID
A	0-0.6	0.3
AB	0-2	1.0
B	0.6-0.2	1.3
C	2-3	2.5
D	3-8	5.5
E	8 and above	8.0
Missing Data	N/A	0.1



Topographic Factor, LS_{USLE}

The topographic, length-slope factor is the expected ratio of soil loss per unit area from the area of interest to that of an experimental 22.1 m slope of uniform 9 percent slope under otherwise identical conditions. LS_{USLE} for each land use type within a catchment may be calculated as follows:

$$LS = (0.045 X_k)^b (65.41 \sin^2 \theta_k + 4.56 \sin \theta_k + 0.065) \quad (E.13)$$

$$\theta_k = \tan^{-1}(ps_k / 100) \quad (E.14)$$

in which X_k is the slope length (m) and PS_k is the percent slope. The exponent in Equation E.13 is given by $b = 0.5$ for $PS_k \geq 5$, $b = 0.4$ for $5 < PS_k < 3$, $b = 0.3$ for $3 \leq PS_k \leq 1$, and $b = 0.2$ for $PS_k < 1$ (Wischmeier & Smith, 1978).

2.1.3 Garrilovic Method of Sediment Loads

A second sediment loading calculation based on equations from Garrilovic (1959) and modified by Zemljic (1971) was used to evaluate sediment loads. The Garrilovic and Zemljic equations are as follows:

$$G = W R \quad (E.15)$$

Where G is the annual sediment volume (m^3/year)

W is the potential annual average sediment yield by surface erosion (m^3/year) (given by E.16)

R is the redeposition or sediment retention coefficient (given by E.19)

$$W = T \times H \times \pi \times Z^{1.5} \times F \quad (E.16)$$

where T is the coefficient of temperature (given by E.17)

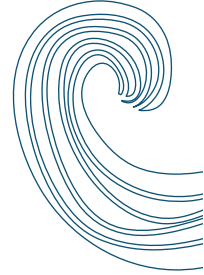
$$T = (t/10 + 0.1)^{0.5} \quad (E.17)$$

where t is the annual average temperature ($^{\circ}C$)

H is the average annual precipitation (mm/year)

F is the basin area (km^2)

Z is the coefficient of erosion (given by E.18.)



$$Z = X Y [\phi + J^{0.5}] \quad (E.18)$$

where X is the coefficient of land use

Y is the coefficient of soil resistance

ϕ is the coefficient of observed erosion

$$R = \frac{(O \times D)^{0.5} (L + L_i)}{(L + 10) \times F} \quad (E.19)$$

where O is the perimeter of the basin (km)

D is the elevation difference between mean and minimum elevation (km)

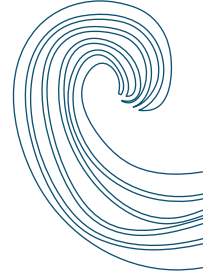
L is the length of the main stream channel (km)

L_i is the length of secondary waterways (km)

F is the basin area (km²)

The sediment volume is multiplied by the density of wet-packed sand (2.7 tonnes/m³) to yield the sediment load. These equations differ from MUSLE by calculating loads on an annual basis, and are not based on daily runoff data. The inputs include climate data as well as soil and land use and land management characteristics. These equations also differ from the MUSLE method by accounting for the portion of the load that is redeposited within the basin through a sediment retention function. The procedure for estimating sediment load using the Gavrilovic method is as follows:

- Calculate erosion coefficient (Z) based on catchment type from user inputs—add these values to the catchments table
- Calculate annual variables by year for each catchment in a run: temperature coefficient (T) and average annual precipitation (h) to yield the potential sediment load for each catchment by year (W)
- Multiply W and the redopostion coefficient (R) to yield the actual annual sediment load for each catchment, G
- Sum values of G for each catchment in the run to yield a total load at the outlet catchment of the run
- The output of the sediment computation is annual sediment load (tonnes/year)



2.1.4 Gavrilovic Sediment Parameters

The coefficient of land use (X) describes the ability of the land use to resist erosion through vegetation or artificial coverage. The coefficient of soil resistance (Y) represents the ability of soil to represent erosion due to precipitation and is generally estimated through laboratory experiments or field measurements. ϕ represents the degree to which active erosion processes are present. Values for X, Y, and ϕ can be seen from **Tables 2-5a through 2-5c**, respectively (adapted from Gavrilovic, 1988).

Table 2-5a. X Parameter Values by Land Use Category

Category	Subcategory	X Value
Areas without vegetation cover	Denudated unarable lands (badlands)	1.00
	Fields ploughed up/down the hill	0.90
Damaged pasture and cultivated land	Orchards or vineyards without low vegetation	0.70
	Field contour-farmed	0.63
	Degraded forestland shrub on eroded soil	0.60
	Dry mountain pastures	0.60
Damaged forest and bushes, pasture	Meadows and similar perennial crops	0.40
Coniferous forest with little grove, scarce bushes, bushy meadows	Grass-grown and drained pastures	0.30
Mixed forests and dense brushes, sparse forests with underwood	Good forest on steep slopes	0.20
	Good forest on gentle slopes	0.05

Table 2-5b. Y Parameter Values by Soil Category

Category	Subcategory	Y Value
Fine sediments and soils poorly resistant to erosion	Sand gravel and loose soil	2.00
Sediments, moraines, clays and other weak rocks	Loess, tuff, saline soil, steppe soil and the like	1.60
	Weather limestone and marl	1.20
Soft rocks, stabilized (talus slope, schists, stiff clays)	Serpentine, red sandstone, flysch deposits	1.10
	Podzol, parapodzol, disintegrated schist, maschist, gneiss, argillaceous schist, etc.	1.00
Rocks partly resistant to erosion	Compact and schistose limestone, tera rossa and fumose-silicate soils	0.90
	Brown forest soil and mountain soils	0.80
	Smonitsa, valley and back bog soils	0.60
Hard rocks resistant to erosion	Chernozem and alluvial deposits of good texture	0.50
	Bare compact igneous rocks	0.25

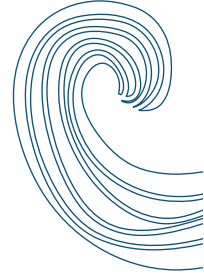


Table 2-5c. ϕ Parameter Values by Basin Category

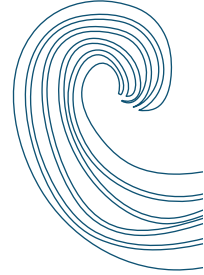
Category	Subcategory	ϕ Value
Fully eroded basin with gullies and landslides	Basin or area fully attached by gulling and deep processes of erosion	1.00
	About 80% of area under rills and gullies	0.90
50-80% of the catchment with rill erosion and landslides	About 50% of area under rills and gullies	0.80
	Entire area attached by surface erosion, detritus and debris, few rills and gullies (deep erosion), and heavy karst erosion	0.70
Sheet erosion, talus debris, slope with rills and gullies, karst erosion	Entire area attached by erosion but without visible deep effects (rills, gullies, rockfalls, etc.)	0.60
	50% of area attached by surface erosion while the rest of the basin is unattached	0.50
Sheet erosion on 20-50% of the catchment	20% of area attached by surface erosion and 80% unattached	0.30
	Land surface without visible erosion effect, minor rockfalls or slips in stream channels	0.20
Low erosion signs in the basins	Land surface without visible erosion effect, mostly crop fields	0.15
	Land surface without visible erosion effect, mostly under woods or perennial crops (meadows, pasture, etc.)	0.10

2.2 Reservoir Simulations

Reservoirs are modeled as discrete objects located at the outlet of a catchment. Hydro-BID routes flow to the catchment containing the reservoir and calculates reservoir releases according to a set of algorithms.

The general procedure used in Hydro-BID consists of:

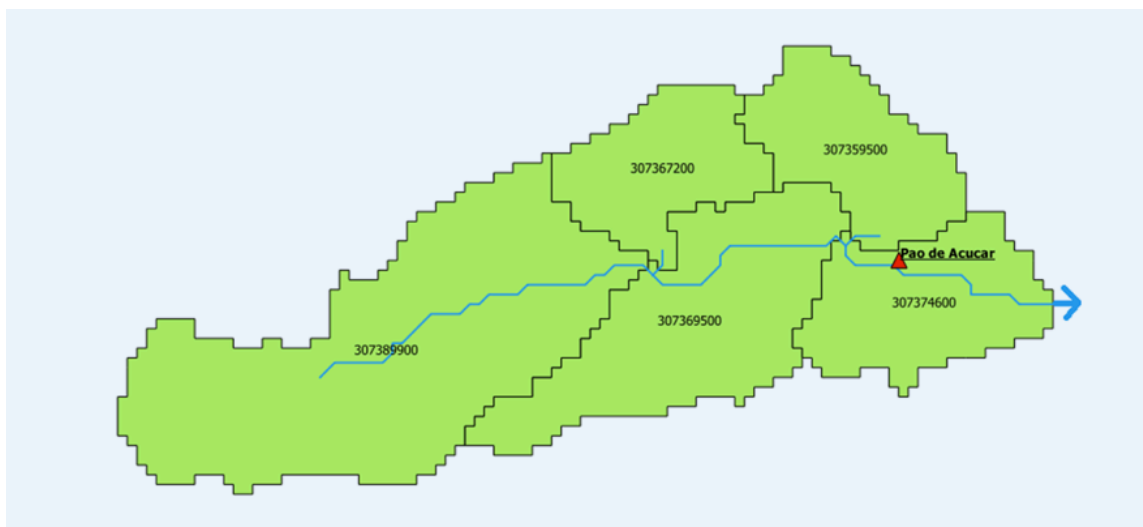
- A reservoir is identified by the catchments (COMID) located at the reservoir outlet.
- Hydro-BID is run and the time series of flow at the outlet of COMID is generated.
- The generated time series will be input to the reservoir module.
- The reservoir model subroutine is run with the inputs: inflow time series, demand, evaporation, and seepage and will produce modified outflow (reservoir releases) and reservoir volume for the COMID.
- Hydro-BID continues run for the downstream by assuming the COMID as a control structure and uses the modified outflow from the reservoir as inflow to the immediate downstream catchment.



- The set-up will work for single or multiple reservoirs within the basin.
- The reservoir storage time series will be used to generate reservoir reliability.

Consider the following example watershed for the Pao de Acucar reservoir in the Ipojuca River basin of Brazil (**Figure 2-1**).

Figure 2-1. Example Watershed for Pao de Acucar Reservoir



Note: Catchments are labelled with COMID.

The reservoir location is specified by the COMID of the reservoir outlet (307374600 in this instance). Flow is routed into this catchment using the rainfall-runoff model in Hydro-BID. The reservoir module in Hydro-BID will calculate release and storage for each time step according to the reservoir release option specified in setup.

The water balance in the reservoir is computed as follows:

$$S_{t+1} = S_t - I_t - R_t - D_t - E_t - L_t \quad (\text{E.20})$$

Where S_t is the storage at time t , calculated in the previous time step

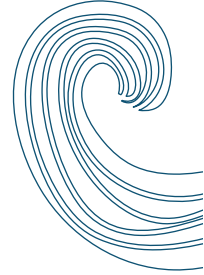
I_t is the inflow at time t , calculated as the inflow to the specified COMID

R_t is the reservoir release (outflow) at time t , calculated by the release option

D_t is the reservoir demand (withdrawn directly from the reservoir) at time t

E_t is the evaporation loss at time t

L_t is the seepage losses at time t



2.2.1 Reservoir Module Parameterization

All reservoirs require the below parameters to be defined in the main Reservoir Database interface:

Labels

COMID is the AHD catchment ID for the catchment containing the reservoir outlet. Hydro-BID models all reservoir operations, including groundwater seepage and evaporation, in this catchment. This can be found using a QGIS tool. Additionally, the reservoir should be given a **Name** for data organization.

Physical Parameters

Shape Parameters are used to determine the relationship between reservoir volume and surface area, which is in turn used to estimate evaporation losses. Two parameters, a and b, are required for establishing the relationship as shown in Equation E.21:

$$\text{Surface area} = \mathbf{b} * (\text{Volume})^{\mathbf{ea}} \quad (\text{E.21})$$

If these values are unknown, default values of -1 for a and -2 for b are suggested.

The **Evaporation Coefficient** is used to scale potential evaporation for an entire reservoir. Potential evaporation is determined from an empirical function of meteorological variables on a daily time step. If an evaporation coefficient is unknown, a default value of 1.2 is suggested.

Hydraulic Conductivity represents the ease with which water flows through the soil media underneath the reservoir and is used to calculate seepage losses from the reservoir. This value is an intrinsic soil property.

Storage Capacity

Reservoir storage in Hydro-BID is classified into two categories: **Principal Volume** and **Flood Volume**. **Principal Volume** can be considered the accessible volume in a reservoir; generally corresponding to the volume of water in the reservoir when water level is at the bottom of the primary spillway. **Flood Volume** can be considered the maximum normal storage volume in a reservoir. This is typically the volume when water level is at the bottom of the spillway. The two volumes and their relationship with reservoir stage are illustrated in **Figure 2-2**.

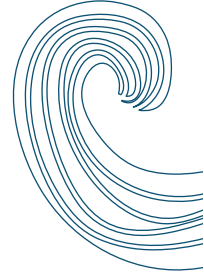
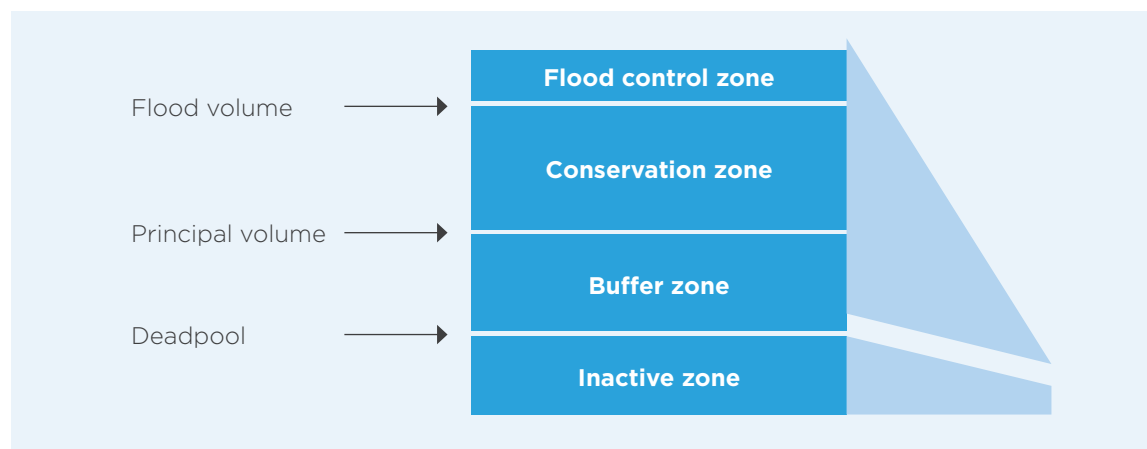


Figure 2-2. Reservoir Storage Zones



Defining Releases

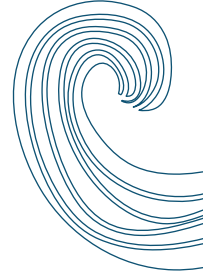
Hydro-BID has two modes for simulating reservoir operations, known as “options” in the user interface. Each option has a unique set of parameters used for modeling desired operations. Before implementing a reservoir in Hydro-BID, the operation goals must be decided. The sections below outline the two options available.

Option 0—Standard Linear Operating Procedure

Standard Linear Operating Procedure (SLOP) is a commonly used, flexible technique for modeling reservoir operations. SLOP is best used for operations that involve meeting a downstream target demand, maintaining a minimum downstream flow, or keeping reservoir storage levels below an allowable maximum value.

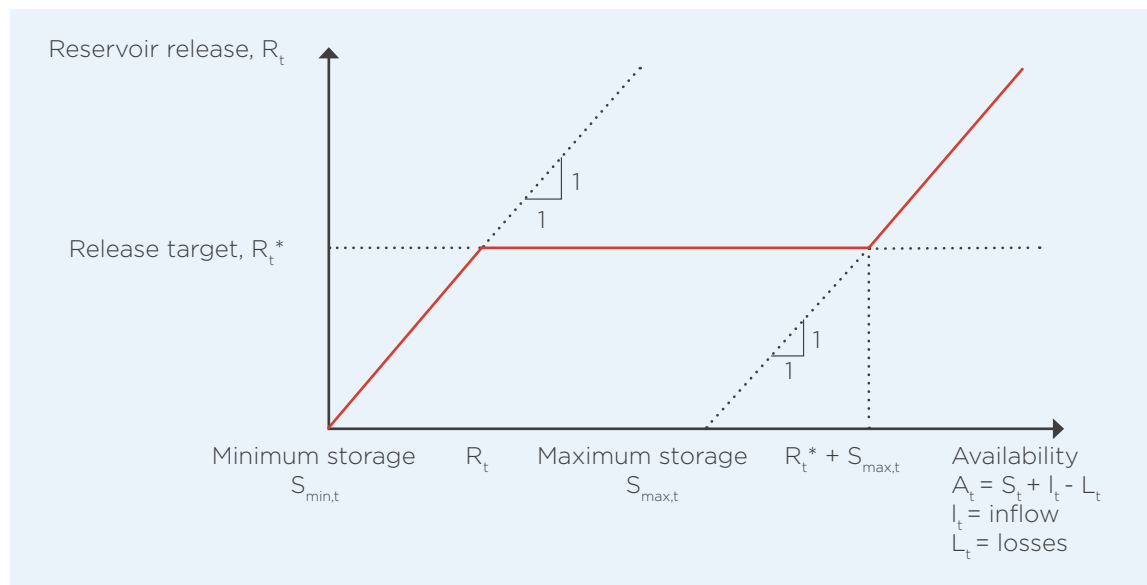
Implementing SLOP requires the following parameters defined in Hydro-BID’s Reservoir Database view:

- **Target Outflow/Release (m³/day):** The desired amount of water daily leaving the reservoir on a given day, defined by month. In Hydro-BID, this is shown as ***min_daily_flow*** in the Monthly Reservoirs database interface. This could be the downstream water demand to be met or a minimum flow requirement.
- **Maximum storage (million m³):** The highest volume of water allowed in a reservoir, defined by month. In Hydro-BID, this is shown as ***target_storage*** in the Monthly Reservoirs database interface. This value often equals the maximum storage volume for which the principal spillway can be used without the flood spillway.
- **Minimum storage (million m³):** The lowest volume of water allowed in a reservoir. In Hydro-BID, this is known as ***principal_vol*** and is found in the Annual Reservoirs database interface.



These parameters are implemented using a linear algorithm that ensures target outflows are released in all situations where enough storage is available, while conserving surplus storage to ensure future demands can be met. The operating rule, defined in terms of storage and inflow is graphed in **Figure 2-3**.

Figure 2-3. Standard Operating Procedure, Highlighted in Red



Option 2—Maintain Target Storage

This reservoir option maintains a target storage volume for a reservoir, specified for each month. This option is best used for maintaining a constant head for hydropower and recreation. This option also provides an effective model in the absence of a known daily target release.

This reservoir release rule requires the following parameters defined in Hydro-BID's Reservoir Database view:

- **Target storage (million m³):** The desired volume of water allowed in a reservoir, defined by month. In Hydro-BID, this is shown as **target_storage** in the Monthly Reservoirs database interface. This value often equals the maximum storage volume for which the principal spillway can be used without the flood spillway.
- **Time to reach target storage:** The number of days after the beginning of a month before a reservoir must reach target storage. This is known as **num_days_target** in the model. For example, if the parameter is 4 and a reservoir has 1,000 m³ of storage over the target storage, 250 m³ will be released each day for the first 4 days of the month to reach target storage levels.

Note that Option 0, SLOP, simplifies to Option 2 when demand target is set to zero.



The specific methods for implementing reservoirs in Hydro-BID can be found in Section 3.4

Reservoir Output

Once a reservoir is implemented in Hydro-BID, performance in meeting the demand can be evaluated with statistics. The following statistics are displayed in the output window under “Reservoir Statistics:”

Time Reliability (monthly and annual) is a measure of how often a reservoir meets or fails to meet target demand. Values close to one indicate a reservoir reliably meets target demands. The value is provided for both monthly and annual time-scales. It is calculated as:

$$\text{Time Reliability} = \frac{\text{Number of time periods in which demand was met}}{\text{Total number of time periods}} \quad (\text{E.22})$$

Volume Reliability represents the total proportion of demand that is not met across all time periods. A value of one indicates that all demand is met. The value will only be less than one if Time Reliability is less than one. Volume reliability is calculated as:

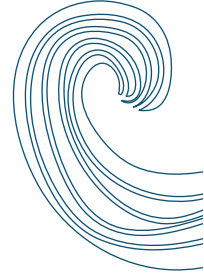
$$\text{Volume Reliability} = 1 - \frac{\text{Total target demand} - \text{Total demand met}}{\text{Total target demand}} \quad (\text{E.23})$$

Resilience represents how quickly a reservoir recovers from failure events. It is calculated over the entire time period as:

$$\text{Resilience} = \frac{\text{Number of time periods in which demand was met}}{\text{Total number of time periods}} \quad (\text{E.24})$$

Vulnerability is a measure of how sensitive a reservoir is to failures. Values closer to zero indicate low vulnerability. The value is calculated over the entire modeled time period as:

$$\text{Vulnerability} = \frac{\text{Sum of maximum shortfall during each failure period}}{\text{Number of continuous sequences of failure}} \quad (\text{E.25})$$



2.3 Groundwater Modeling

This section summarizes RTI's approach for integrated groundwater and surface water availability modeling within Hydro-BID. Integrated modeling enables the assessment of current and future water availability scenarios reflecting the entire water budget (e.g., what short or long-term impacts on surface water availability may result from increased or decreased dependence on groundwater?).

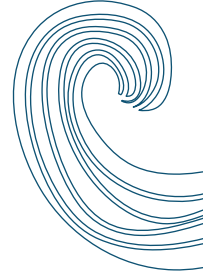
The integrated modeling approach relies upon sufficient characterization of the simulated groundwater system, including the geologic framework, groundwater elevation data, groundwater pumping data, and hydrogeologic properties. For the pilot project for this aspect of Hydro-BID, an existing model of the Piura basin was used. This model was developed by Ricardo Turkowsky Castagnola,² a consultant to the Instituto Nacional de Recursos Naturales and Intendencia de Recursos Hídricos. The model was developed using the USGS groundwater flow model MODFLOW (Harbough et al., 2000). This model formed the basis of the groundwater simulations with some model modifications documented below.

Background

A basic understanding of the water cycle indicates that groundwater and surface waters interconnect and represent a combined water resource. Yet, water resource assessments traditionally have considered groundwater and surface water independently. With abundant supplies, this division has not often mattered. However, in the face of expanding populations and development, water supply pressures are increasing even in many areas traditionally considered water rich. Independent assessment of groundwater and surface water can lead to problems such as double counting and overallocation of the water resource. Appropriate management of stressed water resources must consider the combined water resource and must represent groundwater and surface waters and their interaction. Hydrological models of integrated surface and subsurface processes (the entire water budget) should be developed to quantify impacts of such stresses and also to evaluate interactions between the surface water and groundwater systems.

Surface water models typically include simplified representations of local groundwater flow such as one or more compartments describing subsurface storage (e.g., SAC-SMA, GWLF) or an idealized representation of subsurface flow (e.g., TOPMODEL). Surface water models generally have more detailed representation of surface and shallow subsurface processes such as runoff, infiltration, and evapotranspiration. In contrast, groundwater models (e.g., MODFLOW)

² Ricardo Turkowsky Castagnola, April 2006, Modelamiento Matematico del Acuifero del Valle Alto Piura para la Evaluacion de la Oferta de Aguas Subterranas y su Asignacion para la Formalizacion de Derechos de Uso de Agua.



often emphasize detailed three-dimensional subsurface conditions and heterogeneous hydraulic characteristics; however, groundwater models typically are based on simplified descriptions of surface hydrology with surface processes often characterized only by long-term recharge rates.

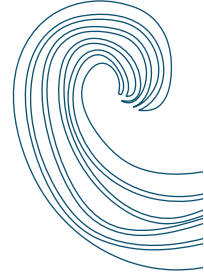
Independent modeling of surface water and groundwater can have advantages if one of the two resources is dominant. For example, in areas where only surface water is utilized, modeling the surface water to account for a high frequency variation of precipitation and corresponding runoff generation is essential. In areas where water usage is dominated by pumping from deep groundwater systems, a comprehensive representation of the subsurface geology and regional recharge by groundwater model is appropriate.

However, water resource development increasingly is reliant on both surface and groundwater resources. Simultaneous reliance on both resources can lead to interactions between the two systems that cannot be represented adequately in independent surface and groundwater models. Therefore, an integrated surface water and groundwater model is required to account for 1) water abstraction from both surface water and groundwater and 2) dynamic interactions (feedback) between surface water and groundwater regimes.

Existing methods to simulate dynamic groundwater and surface water interactions can be categorized either as 1) the fully integrated approach or 2) the coupled-regions approach (Markstrom et al., 2005). The fully integrated approach represents surface water and groundwater flow dynamics through fully coupled differential equations that are solved simultaneously (Panday and Huyakorn, 2004). This approach requires very detailed characterization and small-scale spatial and temporal resolution, thereby limiting its potential applicability in many cases. The coupled-regions approach involves the use of a surface water model to simulate the surface domain and the use of a groundwater model to simulate the groundwater domain, while coupling the models through common terms (e.g., surface water infiltration equals groundwater recharge).

The coupled-regions approach was used to develop the USGS GSFLOW model (Markstrom et al., 2005). GSFLOW is based on coupling of two existing models, the Precipitation-Runoff Modeling System (PRMS) surface water model (Leavesley et al., 2005) and the MODFLOW groundwater model (Harbaugh et al., 2000). GSFLOW simulates flow within and among three regions. The first region is bounded on top by the plant canopy and on the bottom by the lower limit of the soil zone; the second region consists of all streams and lakes; and the third region is the subsurface zone beneath the soil zone. PRMS simulates hydrologic responses in the first region and MODFLOW-2005 simulates hydrologic processes in the second and third regions. Coupling between models is accomplished by running simulations iteratively until the results converge.

Our approach is similar to GSFLOW but with important differences. We link the surface water model Hydro-BID with the groundwater model MODFLOW. Hydro-BID represents the surface watershed and local subsurface (unsaturated and saturated) flow at a small catchment level while MODFLOW represents regional

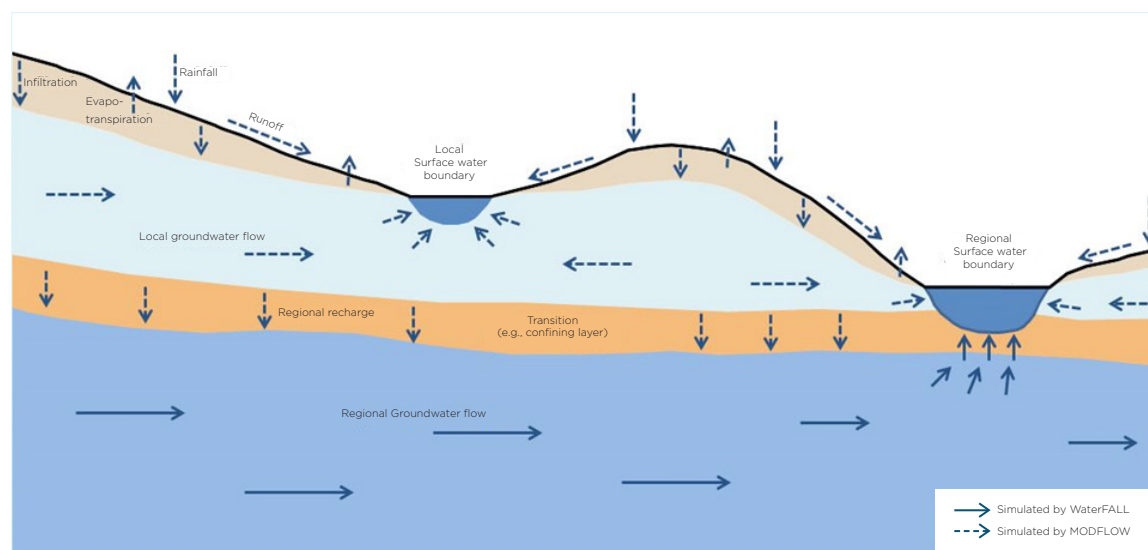


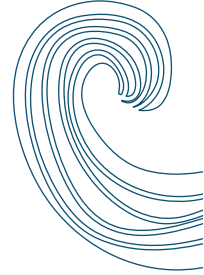
groundwater flow. We have adopted simplifying assumptions that make the approach more readily implemented for large-scale systems when compared with GSFLOW and similar methods. For example, less detailed information is required to characterize local-scale groundwater systems. In addition, the mathematics of our approach provides a more robust and efficient solution when compared with other integrated models, which often have significant numerical stability and runtime issues. Although our approach will not resolve local-scale details as well as other methods (e.g., shallow groundwater levels), it characterizes regional-scale water availability dynamics based on interacting groundwater and surface water systems.

Integrated Modeling Approach

The methodology for integrated surface water and groundwater water availability assessment involves linking Hydro-BID with MODFLOW. **Figure 2-4** illustrates the components of the water cycle simulated by Hydro-BID and MODFLOW, respectively. Hydro-BID represents rainfall, runoff, infiltration, and local groundwater flows, whereas MODFLOW represents regional groundwater flows and discharges. Accordingly, local surface water boundaries that do not interact significantly with the regional groundwater flow system will not be included in the MODFLOW model. Rather, MODFLOW will simulate relatively larger surface water bodies that are significant recharge/discharge boundaries for regional groundwater flow. This discussion begins with a summary description of the Hydro-BID and MODFLOW models followed by a description of the approach for integrating them.

Figure 2-4. Water Cycle Representation within the Integrated Groundwater-Surface Water Availability Model

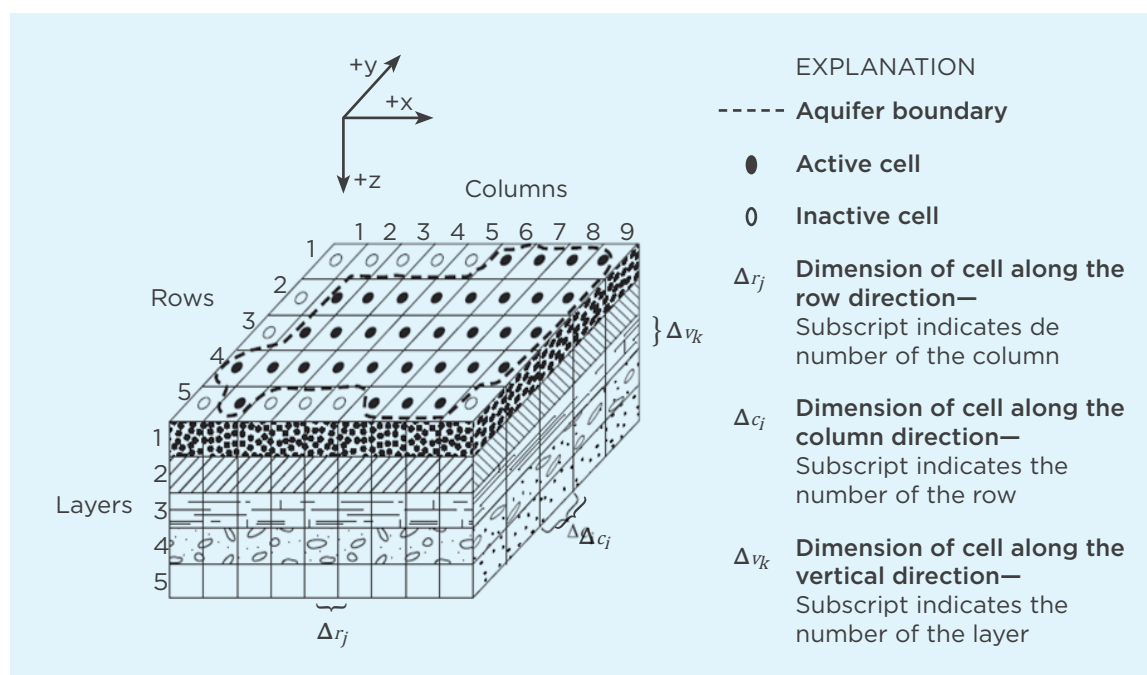




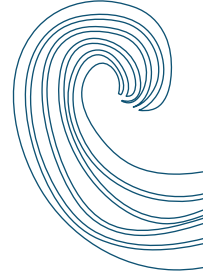
Overview of MODFLOW

MODFLOW is a three-dimensional model of groundwater flow developed by USGS and first published in 1984. The model has a modular structure that allows for extensions and adaptations for a wide range of groundwater conditions; many capabilities have been added to the original model. MODFLOW simulates steady state or transient groundwater flow. The model domain can be irregularly shaped aquifer layers that can be confined or unconfined. External stresses on the aquifer can include pumping or injection from or to wells, areal recharge, evapotranspiration, flow to drains, and flow to or from rivers. Hydraulic conductivity and other parameters (e.g., specific storage) can vary spatially within the model domain. The finite-difference method is used to solve the groundwater flow equation, whereby the model domain is subdivided into grid cells within which properties are assumed to be uniform. The size of grid cells can be small or large scale (e.g., to represent local to regional scale flows and heterogeneities). A MODFLOW grid consists of mutually perpendicular lines that can be variably spaced. Model layers can have varying thickness. **Figure 2-5** illustrates a model grid with active and inactive cells and five layers. The finite-difference approach involves developing coupled flow equations (one for each grid cell) and solving the resulting matrix representation of the flow problem. Several solvers are provided with MODFLOW, offering alternative numerical methods to solve the matrix equations. The distribution of hydraulic heads, flow rates, and mass balances are solved for each time step.

Figure 2-5. Illustration of a MODFLOW Grid with Five Layers



Source: Markstrom et al., 2005.



Integrated Modeling Approach

Figure 2-6 illustrates the integrated model components along with the data flows, processing routines, and model predictions. **Table 2-6** summarizes the integrated model components and associated inputs and outputs. The discussion below considers each of the model components.

The Hydro-BID surface water model predicts daily runoff and local groundwater flow to surface water for each AHD catchment within the simulated watersheds. Key inputs to Hydro-BID include rainfall, temperature, delineated AHD catchments, terrain slope, and soil characteristics. Hydro-BID also will estimate daily seepage downward to regional groundwater for each AHD catchment. Regional groundwater flow includes water that does not discharge to the surface water body within the local catchment; rather, regional flows occur within larger groundwater flow systems and may ultimately be extracted or may discharge to other surface water bodies.

Table 2-6. Integrated Model Components, Inputs, and Outputs

Integrated Model Component	Inputs	Outputs
Hydro-BID	Rainfall, temperature, AHD catchments, slope, soils, etc.	Daily results for each AHD catchment: runoff, local groundwater flow to surface water, deep seepage
Groundwater Recharge Processor	Deep seepage	Time series of groundwater recharge for each model grid cell (MODFLOW format)
Surface Water Boundary Processor	AHD features and elevations	Surface water boundary locations and specifications (MODFLOW format)
MODFLOW	Model setup (aquifer geometry, parameters, extraction, etc.), recharge, surface water boundaries	Groundwater elevations Regional groundwater flow to/from surface water
Flow Processor	Runoff, local groundwater flow to surface water, surface water extraction and returns, groundwater extraction, regional groundwater flows to/from surface water	Surface water flows

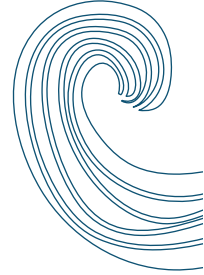
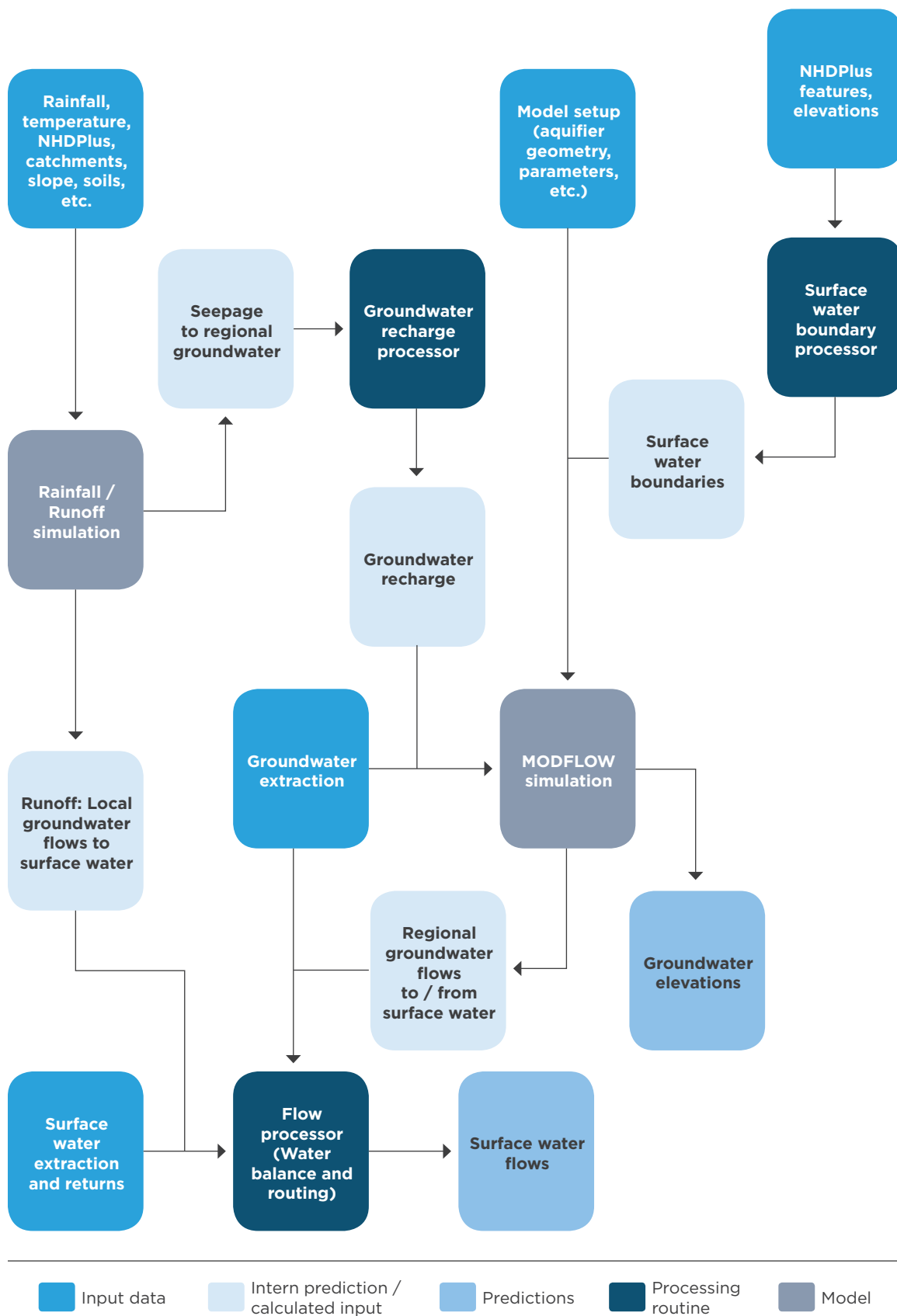
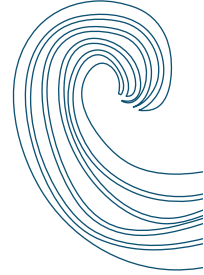


Figure 2-6. Integrated Surface Water and Groundwater Availability Model Simulation and Data Flow Schematic





The groundwater recharge processor converts deep seepage (predicted by Hydro-BID) into groundwater recharge for the groundwater model. This tool develops recharge rates for each groundwater model grid cell based on catchment-specific deep seepage rates. **Figure 2-7** is an example overlay of AHD catchments (shown in orange) with a groundwater model grid (shown in black).

Figure 2-7. Example MODFLOW Grid (black) Overlain onto AHD Catchments (orange)

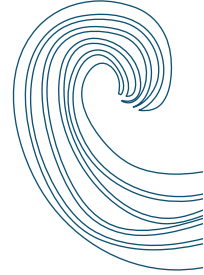


The recharge processor calculates recharge for each groundwater model grid cell through area-weighted averaging of catchment-specific deep seepage rates. The tool creates a MODFLOW recharge package input file for the groundwater flow model. The total recharge is calculated for the time step of groundwater modeling within a catchment and further distributed to grids within the catchment according to the following formula:

$$\text{Recharge} = \sum_t L_t \quad (\text{E.26})$$

Recharge serves as a direct input to MODFLOW.

The surface water boundary processor utilizes AHD surface water features (flow-lines and areas) and associated elevations to create surface water boundaries for the groundwater model. This tool creates a MODFLOW river boundary input file containing the specifications for the surface water boundaries.



The MODFLOW simulation predicts groundwater elevations as well as regional groundwater flow rates to and from surface water bodies. As described above, recharge and surface water boundaries are provided from the integrated model. The remaining groundwater model setup (e.g., aquifer geometry, hydraulic conductivity, specific storage, extraction rates) are developed independently.

The flow processor predicts surface water flows based on surface water routing calculations and the following flow results: 1) surface water extractions and returns, 2) Hydro-BID predicted flows of runoff and local groundwater to surface water, 3) groundwater extraction rates (converted to surface water returns), and regional groundwater flows to and from surface water. This information is compiled and processed to predict surface water flows reflecting the range of inflows and outflows predicted by the integrated model.

2.3.1 Groundwater Parameterization

To link Hydro-BID and MODFLOW, the following parameters need to be specified:

Hydraulic Conductivity Multiplier

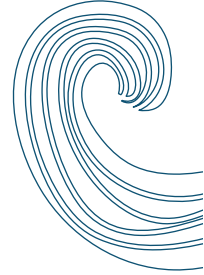
This parameter scales all hydraulic conductivity values in the MODFLOW grid by the specified value. A default value of 1 is recommended.

Stage Multiplier

The Stage Multiplier scales river surface water stage by the specified value. A default value of 1 is recommended.

River Conductance Multiplier

This parameter scales the conductance (connectivity) at the surface water-groundwater interface. High values will accelerate conductance and low values will slow the process. A default value of 1 is recommended.



The Hydro-BID system includes the Analytical Hydrographic Dataset (AHD), the combined Generalized Watershed Loading Factor (GWLF)/RTI lag-routing model, and the graphical user interface (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.

3.1 Hydro-BID Registration

When installing Hydro-BID, by running the file installer.jar. The installation tool will walk through a series of steps to set up Hydro-BID in the desired directory. When the user opens Hydro-BID for the first time, they will be asked to fill out the user information form, shown below in **Figure 3-1**.

Figure 3-1. Hydro-BID User Information Form

This will generate a hash key and instruct them to contact the support center and send the file “user.info” (the folder of this file opens after pressing OK on the instruction message). The support staff will use the Hydro-BID License Validator program, shown below, in **Figure 3-2** to enter a date of expiration (or click the check box for a permanent license) and the hash key provided in the user.info file to generate an encrypted license key. This will be sent back to user with instruction on how to register.

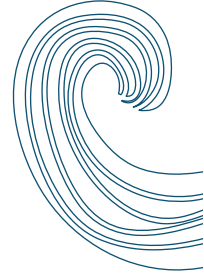


Figure 3-2. Hydro-BID License Validator

The screenshot shows a window titled "Hydro-BID Security". It contains the following elements:

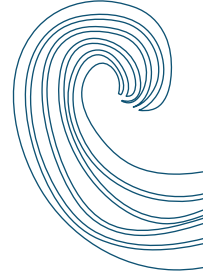
- "Enter expiration date:" followed by a text input field containing "mm/dd/yyyy" and a checkbox labeled "Permanent License".
- "Enter hash string:" followed by a large empty text area.
- A "Generate License Key" button.
- "License Key:" followed by another large empty text area.

Users will have the option to register at any time by going to Help -> Register License and using the field shown below in **Figure 3-3**.

Figure 3-3. Hydro-BID Registration Tool

The screenshot shows a window titled "Registration". It contains the following elements:

- The instruction: "Please copy and paste the license key provided into the field below:"
- A large empty text area for pasting the license key.
- A "Validate" button at the bottom.



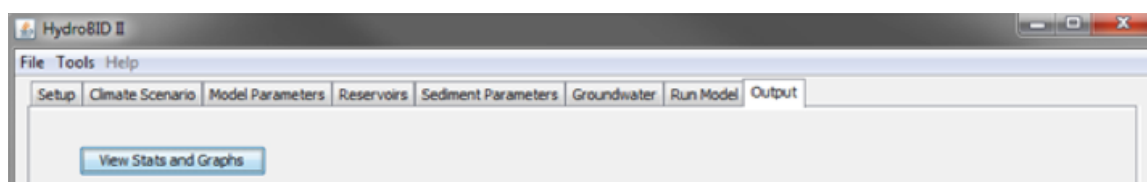
The user will also be prompted to register if not already done 10 days after first use. After the 10 days, the user cannot use the program until they have registered. They will also be notified 2 weeks before their license expires and asked to update their user information and contact their Hydro-BID representative. Then, they can either re-register or get the latest version of Hydro-BID.

3.2 Model Outputs

Hydro-BID generates time series of multiple hydrologic characteristics, including precipitation, base flow, total routed flow, soil moisture storage, and evaporation. These time series are stored in readily usable comma-separated value (.csv) files in the output directory specified during model setup.

Based on the above output and observed flow time series, Hydro-BID can produce visualizations to better understand results. To generate these charts and view summary statistics, navigate to the Output tab in the Hydro-BID window after a successful model run and click View Stats and Graphs, as shown in **Figure 3-4**.

Figure 3-4. Output Tab in Core Hydro-BID Model



Visualizations of model output can be viewed in the other Data Viewer tabs. The Graph tab shows a hydrograph (**Figure 3-5**) and allows other time series to be graphed at the monthly scale and with either log or normal scaling. Along with the new modules, new visualization options were developed to include new output variables like groundwater flow, sediment concentration and reservoir inflow, outflow and volume.

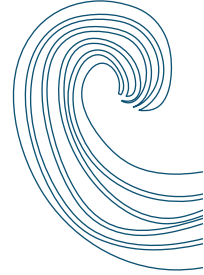
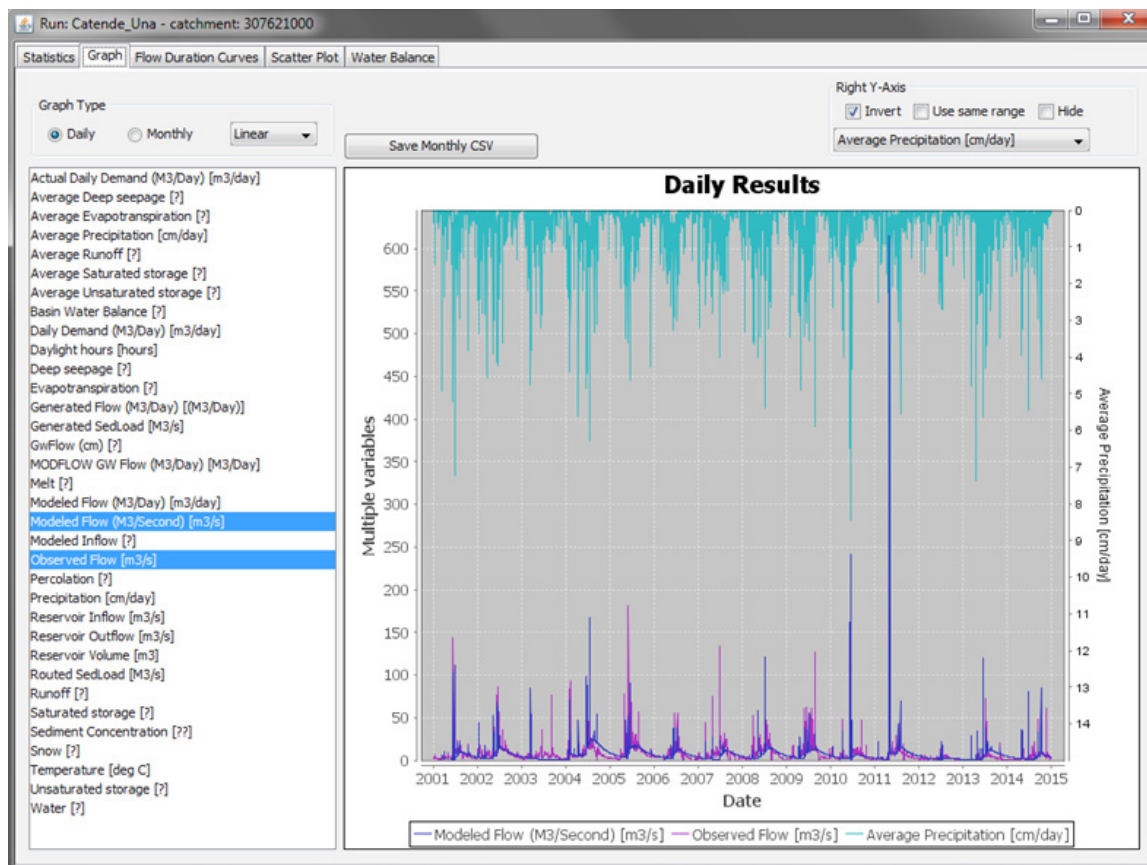


Figure 3-5. Hydrograph with Observed and Modeled Flow



3.3 Hydro-BID Parameters and Modeling Options

In this section, we describe the input parameters for Hydro-BID new modules in detail and introduce several options that are available to model a watershed. Consider again the Setup tab shown in **Figure 3-6** that now includes tabs for the new features (Reservoirs and Groundwater).

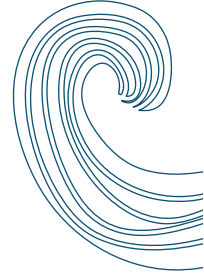
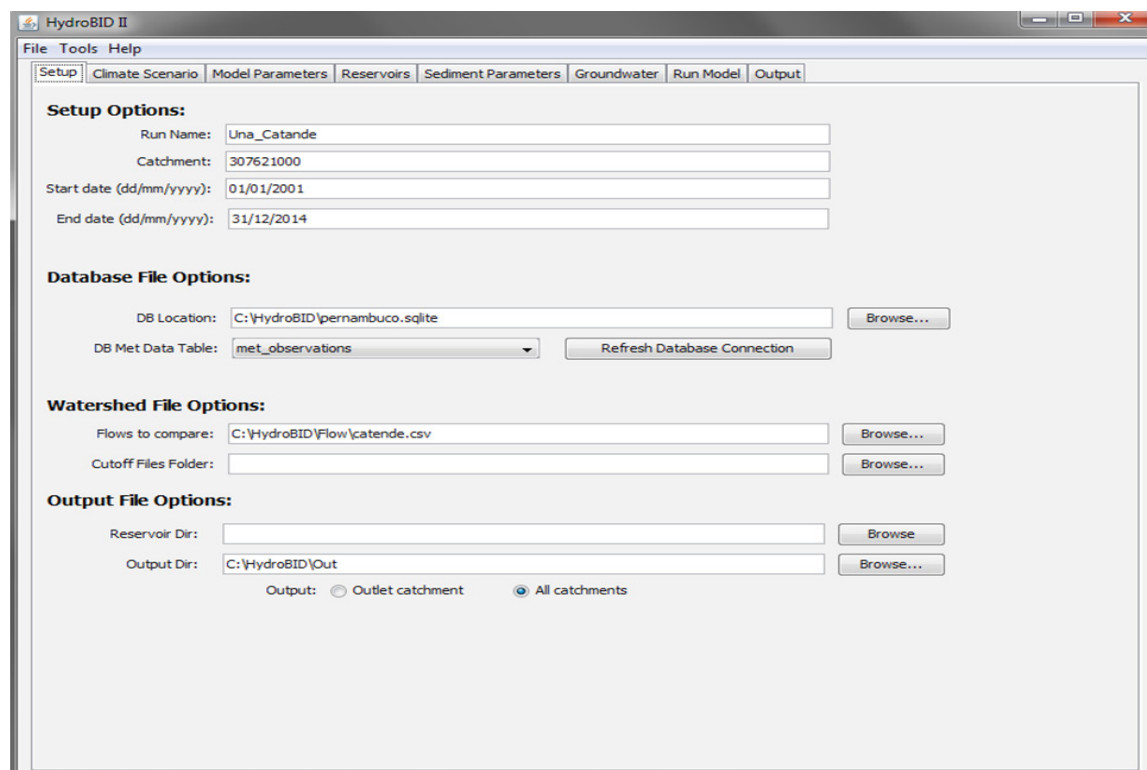


Figure 3-6. Hydro-BID Interface - Setup tab

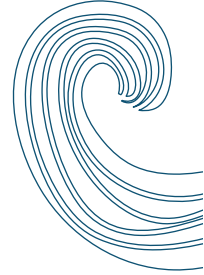


Though Hydro-BID is designed mainly to represent natural hydrological processes, we have enhanced the system to be used in areas where there is significant anthropogenic flow alteration. Such alterations include reservoirs. For instance, if an upper catchment of a large river contains a large reservoir 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. 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.

Hydro-BID generates two sets of output files; catchment time-series and reservoir performance files. The reservoir files are generated in the directory specified as “Reservoir Dir,” with the rest of the model output placed in the “Output Dir.” Note that the reservoir output only occurs if reservoirs are active.

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 3-8**, 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 for each catchment modeled (for example, water supply diversion points), Hydro-BID should be run with the option “All catchments” specified. This will cause the model to output results for all catchments in the basin.

Figure 3-8. Output File Options

Output File Options:

Reservoir Dir:

Output Dir:

Output: Outlet catchment All catchments

The setup parameters shown in the interface above (**Figure 3-6**) are summarized for quick reference in **Table 3-1**.

Table 3-1. Setup Parameters

Setup and File Options:	Description
Run Name	An identifier of run
Catchment	Outlet catchment ID corresponding to the AHD specification (described below)
Start Date (dd/mm/yyyy)	Start date of simulation
End Date (dd/mm/yyyy)	End date of simulation
DB Location	Location of the database (provide full path), example: C:/projects/ca.sqlite
DB Met Data Table	Table name in above database containing interpolated climate data
Refresh Database Connection	Click to confirm Hydro-BID is connected to the project database
Flows to Compare	Input file for observed flow time series. Used for comparison with the simulated flows. See example file for formats.
Reservoir Dir	Location of reservoir output files
Output Dir	Location of output files, example: C:/projects/out

The hydrologic model parameters are described in **Table 3-2**.

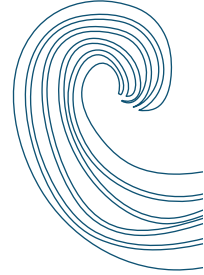


Table 3-2. Hydrologic Model Parameters

Setup and File Options	Description	Suggested Value
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 Capacity: 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
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
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
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.

Calibration Cutoff COMID

The Model Parameters page allows precise control over the spatial extent of a calibration using the cutoff COMID feature on the Model Parameters tab. By default, Hydro-BID applies parameters to all basins upstream of the catchment specified on the setup tab (the entire modeled watershed). However, this may not always be desired, such as in basins with a diverse topography draining multiple types of ecosystems and land cover.

The Calibration Cutoff COMID defines a catchment that serves as the upstream limit for replacing parameter values. If “Replace All” is selected and a value is entered for the Cutoff, parameters will only be overwritten in catchments upstream of the Setup COMID and downstream of the cutoff COMID. Consider the watershed shown in **Figure 3-9**.

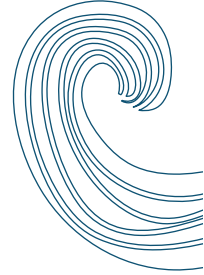
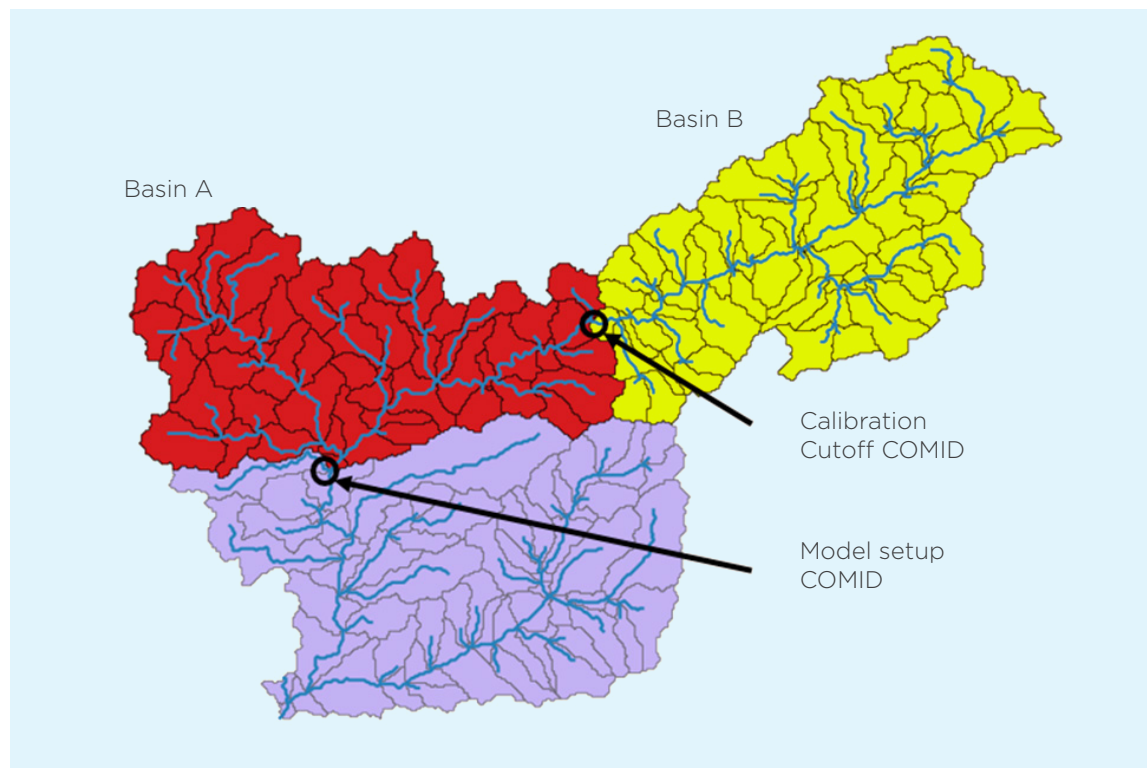


Figure 3-9. Example Cutoff COMID Basin



During Hydro-BID model setup, the catchment at the outlet of the basin is specified as the Model Setup COMID. Both basin A and B drain to this point. However, B is upstream of A. If the Calibration Cutoff COMID is left blank, calibrated values are applied to both basins A and B. However, if the Calibration Cutoff COMID is specified as the outlet of basin B, calibrated values would only be applied to basin A.

This function is also useful for calibrating basins downstream of points that already have a successful calibration. Simply enter the most downstream COMID of the successfully calibrated basin as the Cutoff COMID to prevent overwriting the parameters.

The Calibration Cutoff COMID field is capable of having multiple cutoffs. The COMIDs for each cutoff catchment must be separated by commas.

3.3.1 Setting File

Hydro-BID automatically saves all the settings and parameters from the interface as a text file in the output directory (**Figure 3-10**) named as Runname_setting.txt. The setting file allows an identical re-run of the model at any time in the future. To open an older settings file, navigate to File, then Open... and select the desired Runname_settings.txt file.

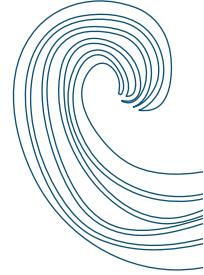
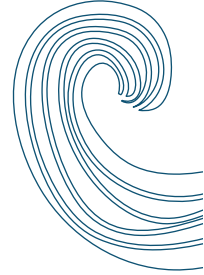


Figure 3-10. Setting File

```
mavel=.5
awc=0.9
cutoffFilesFolder=
temperatureadjustment=0
catchment=313951000
imperviousCover=2
endofgrowingseason=210
dblocation=C:\Projects\LAC-LatinAmerica\Iwrn_ver1\SA.sqlite
rcoefficient=.005
seepage=0.05
growSeasonETCoverFactor=1
precipitationadjustment=0
flowComparisonData=C:\Projects\LAC-LatinAmerica\Iwrn_ver1\San_f:
startofgrowingseason=115
startdate=1/1/2000
climatedata=C:\Projects\LAC-LatinAmerica\Iwrn_ver1\Ref_climate_
dormatSeasonETFactor=1
precipitationmultiplier=0.8
latitude=-30
enddate=31/12/2010
runname=Tes313678200
outputdir=out
awcmultiplier_radio=true
outletcatchment_radio=true
rcoefficientsinglevalue_radio=true
allcatchments_radio=false
useprecipitationadjustments=false
useprecipitationmultipliers=true
```

3.4 Reservoirs

Reservoirs are implemented in Hydro-BID through a database interface. In this interface, users specify parameters for reservoir geometry, physical characteristics, and release rules. To access the reservoir modeling interface, navigate to the Reservoirs tab in Hydro-BID and click the checkbox “Include Reservoirs” as illustrated in **Figure 3-11**.



If no reservoirs are shown when the module is activated, the user will need to manually add them in the interface. **Table 3-3** describes each parameter, with required values underlined>. Note that the parameters in **Table 3-3** are annual values. After a reservoir has been added or removed, or values have been changed, click Save in the upper right-hand portion of the interface to write the changes to the database.

Figure 3-11. Reservoir Modeling Interface

comid	name	shapepara...	shapepara...	option_nu...	evap_coeff	hydraulic...	nonflood_s...	nonflood_s...	number_d...	pri
307153700	Carpina	-1	-2	4	1.1	0.1	10	12	1	1
307204300	Jucazinho	-1	-2	4	1.1	0.1	10	12	1	1
307227300	Goita	-1	-2	4	1.1	0.1	10	12	2	2
307293900	Tapacura	-1	-2	4	1.1	0.1	10	12	2	2
307314700	Serrinha II	-1	-2	4	1.1	0.1	10	12	2	2
307374600	Pao de Acucar	-1	-2	4	1.1	0.1	10	12	2	2
307407400	Belo Jardim	-1	-2	4	1.1	0.1	10	12	2	2
307497400	Barra do Jua	-1	-2	2	1.1	0.1	10	12	2	2
307513400	Prata	-1	-2	4	1.1	0.1	10	12	2	2
307528300	Bonitinho	-1	-2	4	1.1	0.1	10	12	2	2

(Reservoir,
Sediment and
Groundwater
Simulation
Modules)

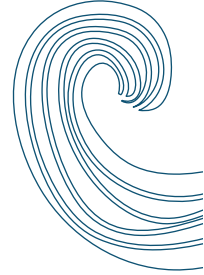


Table 3-3. Reservoir Parameters (annual time scale)

Field Name	Alias/Description (units)	Description	Recommended Default Value
comid	COMID	Outlet catchment ID	N/A
name	Reservoir name	Label for reservoir results	N/A
shapeparameter_a	Shape parameter a	Defines volume-surface area relationship	-1
shapeparameter_b	Shape parameter b	Defines volume-surface area relationship	-2
option_number	Option number	Specifies ruleset governing release rates	2
evap_coeff	Evaporation coefficient	Empirical evaporation coefficient	1.1
hydraulic_conductivity	Hydraulic conductivity (cm/day)	Defines losses to groundwater	0.1
nonflood_season_bein	Non-flood season begin	Monthly number for beginning of non-flood season	10
nonflood_season_end	Non-flood season end	Monthly number for end of non-flood season	12
number_day_target	Number of days to reach target	Number of days available for reservoir to meet monthly storage requirement	15
principal_vol	Principal volume (million m ³)	Minimum useable reservoir volume	N/A
flood_vol	Flood volume (million m ³)	Maximum reservoir volume	N/A
max_surface_area	Maximum surface area extent (km ²)	Surface area of the reservoir at flood volume	N/A
avg_daily_release	Average daily release (m ³ /day)	Average annual daily release	N/A
initial_vol	Initial volume (m ³)	Volume at the beginning of Hydro-BID simulation	N/A
type	Reservoir type variable	Internal variable used by Hydro-BID	2

For more precise reservoir modeling, monthly values can be applied. To set monthly parameters for a reservoir, select the corresponding row in the reservoir interface and click View Monthly. A table will load allowing parameters to be modified as shown in **Figure 3-12**.

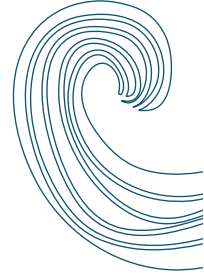


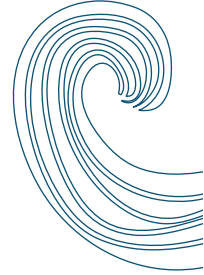
Figure 3-12. Monthly Reservoir Parameters

Month	min_daily_flow	max_daily_flow	target_storage	demand
1	0	150	700	300
2	0	150	700	250
3	0	150	700	250
4	0	150	700	215
5	0	200	700	215
6	0	200	700	215
7	0	200	700	215
8	0	200	700	215
9	0	200	700	215
10	0	200	700	250
11	0	200	700	300
12	0	150	700	300

The columns in the monthly reservoir parameter table are defined in **Table 3-4**. More information can be found on these parameters in Chapter 2.

Table 3-4. Monthly Reservoir Parameters

Field Name [units]	Alias/Description (units)	Description
Month	Numeric value of each month	Numeric value of each month.
min_daily_flow	Minimum daily flow (m ³ /day)	Required minimum release. Can be used to specify downstream demand or environmental flow requirements.
max_daily_flow	Maximum daily flow (m ³ /day)	Maximum permissible release. Generally used to prevent accidental flooding.
target_storage	Target storage (million m ³)	Desired optimal reservoir storage.
demand	Consumptive use	Total demand for consumptive withdrawals from the reservoir.



Reservoir Output

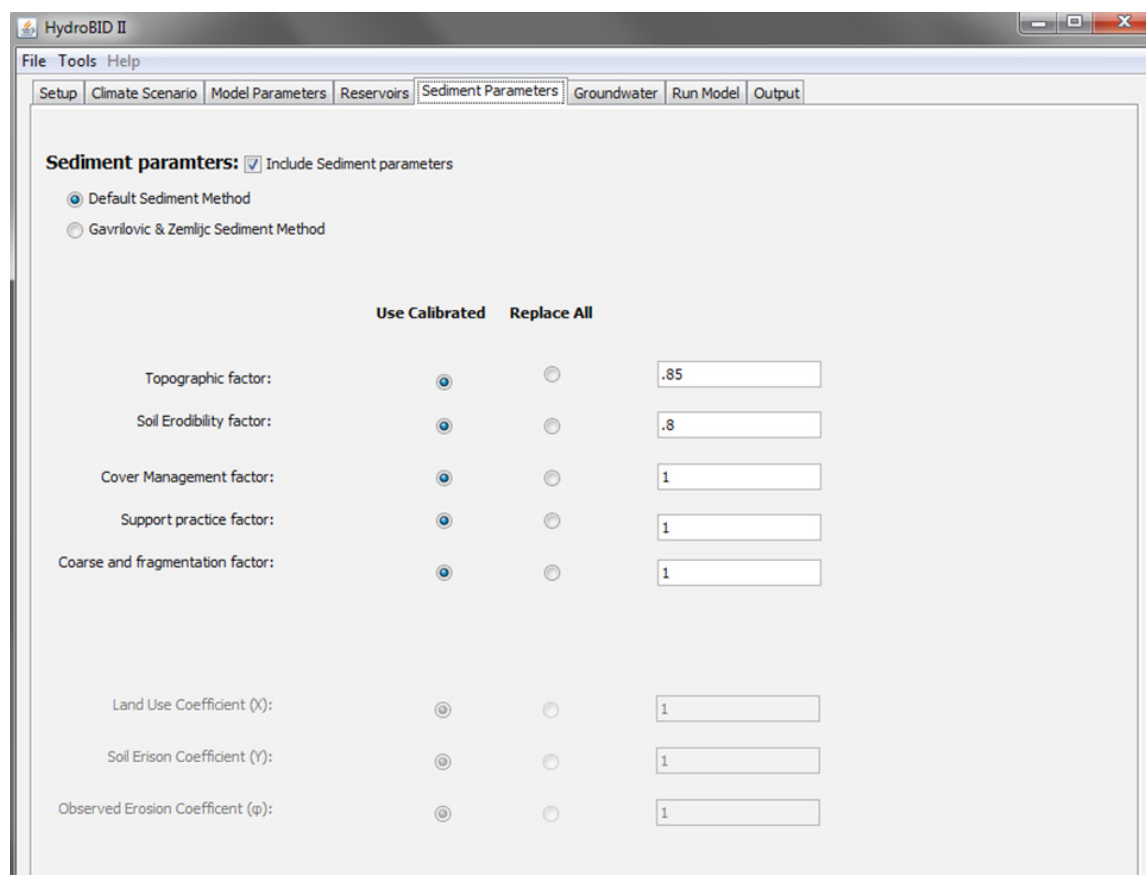
A time-series of reservoir releases, storage, and demand is available in the folder specified as the “Reservoir Dir” on the Hydro-BID setup page. If the “Catchment COMID” specified on the Setup Tab contains a reservoir, the data visualization tab will be able to graph storage, inflow, and releases.

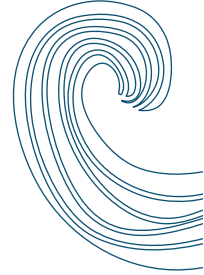
3.5 Sediment Modeling

Sediment modeling is implemented under the Sediment Parameters tab. To activate the module, click the “Include Sediment parameters” checkbox as shown in **Figure 3-13**.

Two sediment calculation methods are present. To activate a method; select the corresponding option under the “Include Sediment parameters” button.

Figure 3-13. Sediment Parameters





Default Sediment Method

The Default Sediment Method is based on the Modified Universal Soil Loss Equation (MUSLE) and provides daily outputs of sediment mass yield by basin. The parameters used are empirical coefficients as approximations of soil properties. More information on these parameters can be found in Chapter 2.

Output from the Default Sediment Method is included in the “-Outlet.csv” file as a daily time series. **Table 3-5** describes the MUSLE output columns.

Table 3-5. Default Sediment Method Output

Field Name (units)	Description
Generated SedLoad [tonnes/day]	Sediment contribution from the outlet catchment
Routed SedLoad (tonnes/day)	Total sediment load exiting the outlet catchment, including all upstream contributions
Sediment Concentration (tonnes/m ³)	Concentration of sediment in output flow

Gavrilovic & Zemljic Method

The Gavrilovic & Zemljic Sediment Method provides annual estimates of sediment yield as volume. More details on the parameters are provided in Chapter 2. Output from the method is found in the output folder in a file named “annual_sed_COMID_OUTLET.csv” where COMID corresponds to the catchment specified under Model Setup. **Table 3-6** describes the columns in the output file.

Table 3-6. Gavrilovic & Zemljic Method Output

Field Name (units)	Description
SedimentLoad G (m ³ /year)	Total sediment volume exiting the catchment annually.
Potential Sediment Load W (m ³ /year)	Intermediate calculation step. See Chapter 2.
R Coefficient	Intermediate calculation step. See Chapter 2.

3.6 Groundwater Modeling

The integrated groundwater and surface water model available through Hydro-BID requires a working MODFLOW model. **Figure 3-14** shows the groundwater tab for the Hydro-BID interface.

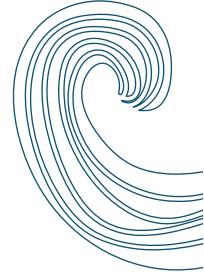
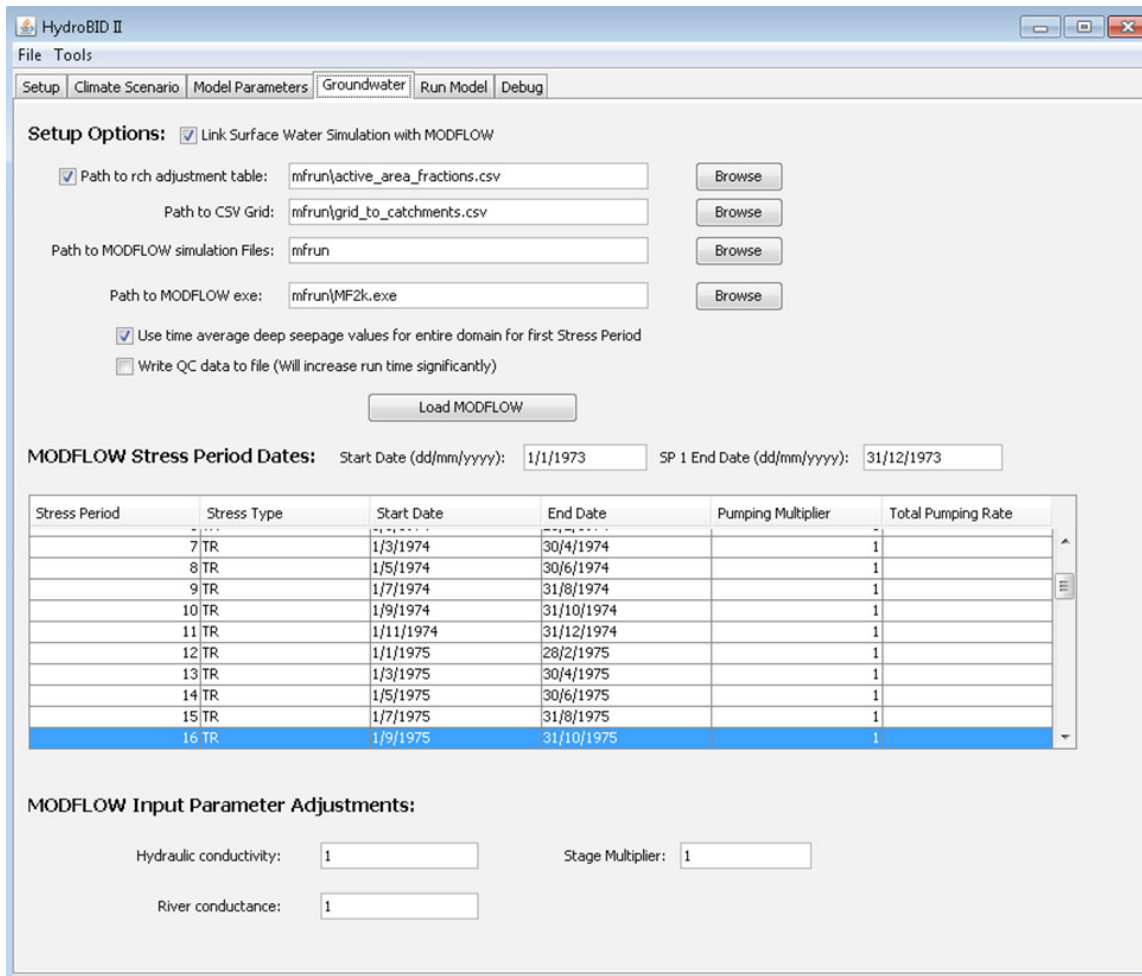


Figure 3-14. The Hydro-BID Integrated Groundwater Surface Water Model Interface



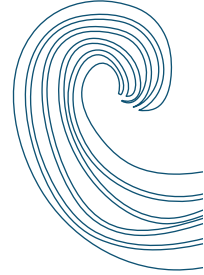
Each of the required inputs is described below.

RCH Adjustment Table

A comma-delimited table containing information catchment geography and adjustment factors for recharges. Each column of the table is described in **Table 3-7a**.

Table 3-7a. RCH Adjustment Table Headers

Column Label	Description
COMID	AHD COMID label for each catchment
area_m2	Total area of the catchment in square meters
act_area	Total area of the catchment in acres
rch_adjust	Adjustment factor for recharge



CSV Grid

A comma-delimited table mapping COMIDs overlying each node of the MODFLOW grid. Each column of the table is described in **Table 3-7b**.

Table 3-7b. CSV Grid Table Headers

Column Label	Description
row	Row number for MODFLOW grid point
column	Column number for MODFLOW grid point
COMID	AHD COMID corresponding to the grid point specified by the above row and column

Path to MODFLOW Simulation Files

The path to all necessary files for running a standalone MODFLOW simulation must be contained in the folder specified here.

Path to MODFLOW.exe

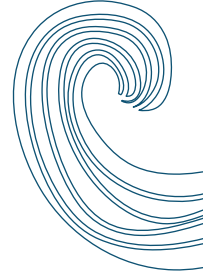
The path to the MODFLOW executable must be specified. Hydro-BID is compatible with both MF2k.exe and MFNWT64.exe versions of MODFLOW.

MODFLOW Stress Period Dates

This table details the stress period, type, start date, and end date as described in the MODFLOW simulation files. The pumping multiplier for each stress period can be adjusted in the table.

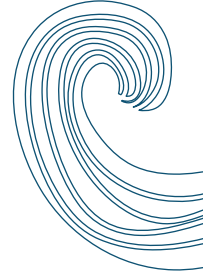
To execute an integrated simulation:

- Check “Link Surface Water Simulation with MODFLOW”
- Check “Path to rch adjustment table” and enter the path to this file. The table should be comma delimited. It should list each catchment’s COMID followed by area of the catchment covered by the groundwater model in square meters and acres. In some cases, the groundwater model only includes part of the catchment area, and these adjustment factors account for the differences.
- Specify the path to the CSV grid.
- Enter the path to the MODFLOW simulation files. This directory should have all of the required MODFLOW input files.
- Enter the path to the MODFLOW executable.



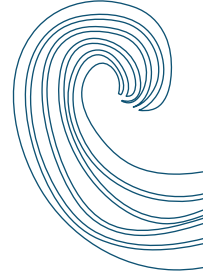
- Enter the start date for the first stress period.
- Click “Load MODFLOW.” This will read the associated MODFLOW setup and populate the table in the Hydro-BID interface with the stress period and date range information.
- Input parameter adjustments are available for MODFLOW for the hydraulic conductivity, the river boundary conductance, and the river stage. These multipliers will be applied to all of the corresponding MODFLOW inputs. Values of 1 should be used to leave the inputs at the original values.
- On the Hydro-BID Run tab, press Go.
- Once the model has completed, click View Stats and Graphs to bring up the Hydro-BID results interface.



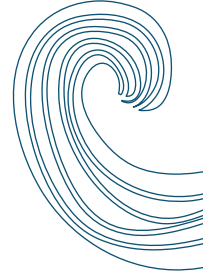


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Appendix A: AHD Navigation Tool — User Guide¹

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



A.1 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; and
- a database structure for populating and attaching additional model-specific attributes.

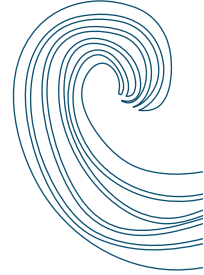
The AHD Tools are designed to assist users with visualizing and navigating on the AHD flowlines and catchments in the Quantum GIS (QGIS) desktop application. The tools include simple menus to allow users to choose what features they want to navigate and then display information about the navigation results.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

A.2 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 2.8. The AHD Tools have been tested in this version of QGIS on the 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 con-

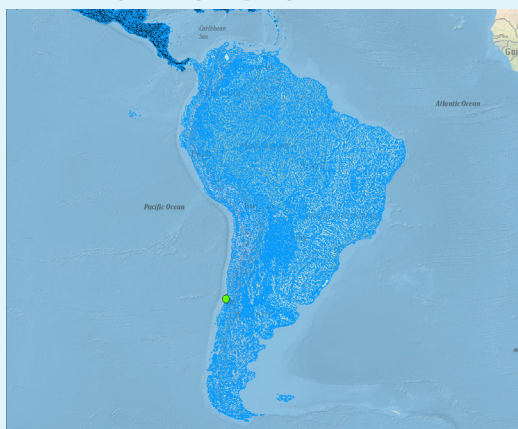


sists of approximately 37,000 catchments and stream segments. The average catchment area is approximately 83 square kilometers, and the average stream segment length is approximately 10 kilometers. The South America AHD consists of approximately 193,000 catchments and stream segments; the average catchment area is 92 square kilometers; and the average stream segment length is approximately 11 kilometers.

Figure A-1. Central America AHD Hydrography

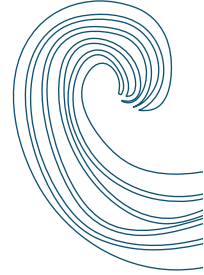


Figure A-2. South America AHD Hydrography



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 (AHD-Flow.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.



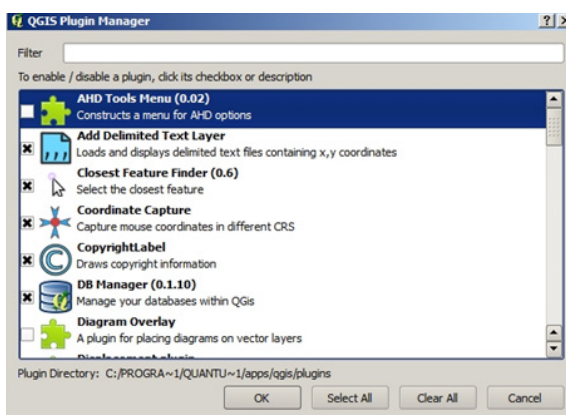
A.3 Installing and Using the AHD Tools (Version 0.03) in QGIS (Version 2.8)

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:\Users\{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. Note: If an “AHD Tools” subfolder already exists before unzipping the file then you should move it or delete it before extracting the new version.

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 (0.03)” 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).

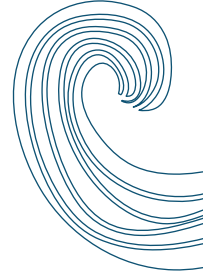
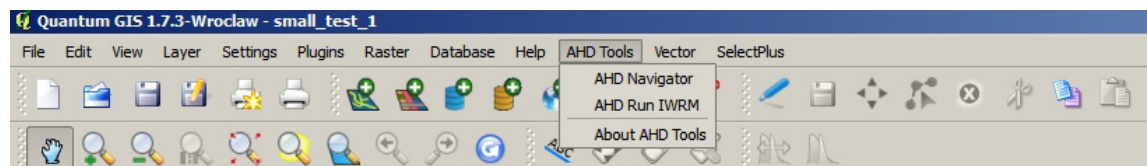


Figure A-4. AHD Tools menu. The AHD Navigator allows navigation on AHD flowlines and catchments.



Click that menu to see the sub-menu with three choices “AHD Navigator,” “Groundwater Data Prep,” and “About AHD Tools.” The Groundwater Data Prep menu is for attaching catchment IDs (COMIDs) to points and is discussed in more detail after the navigation tool.)

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

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).

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.)

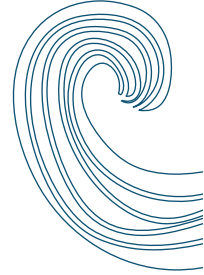
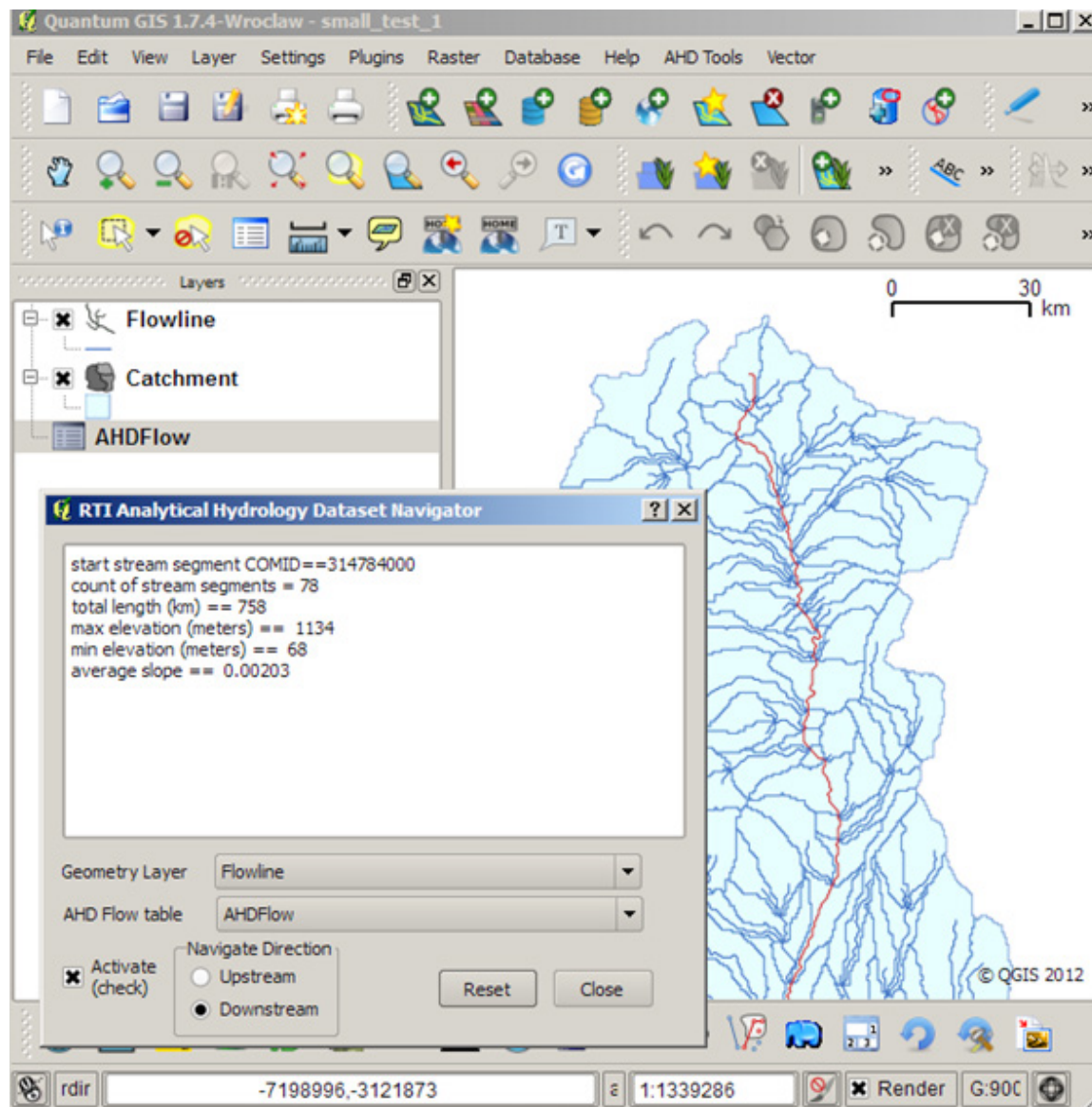


Figure A-5. RTI Analytical Hydrology Dataset Navigator Showing Downstream Navigation of the Flowline



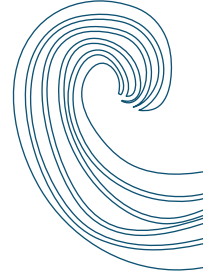
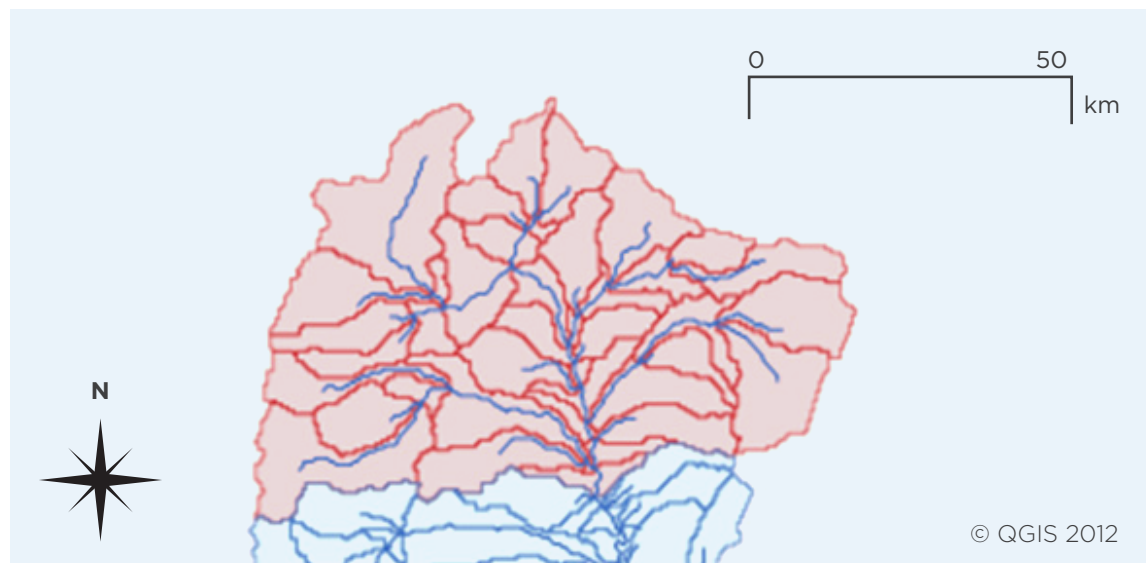


Figure A-6. Upstream Navigation of the Catchment Layer



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).

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**).

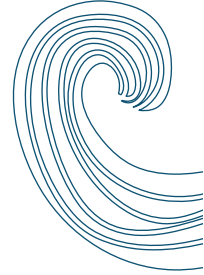


Figure A-7. The upstream part of the basin has been removed from the navigation by holding down the Shift key and clicking a catchment within the previously selected basin

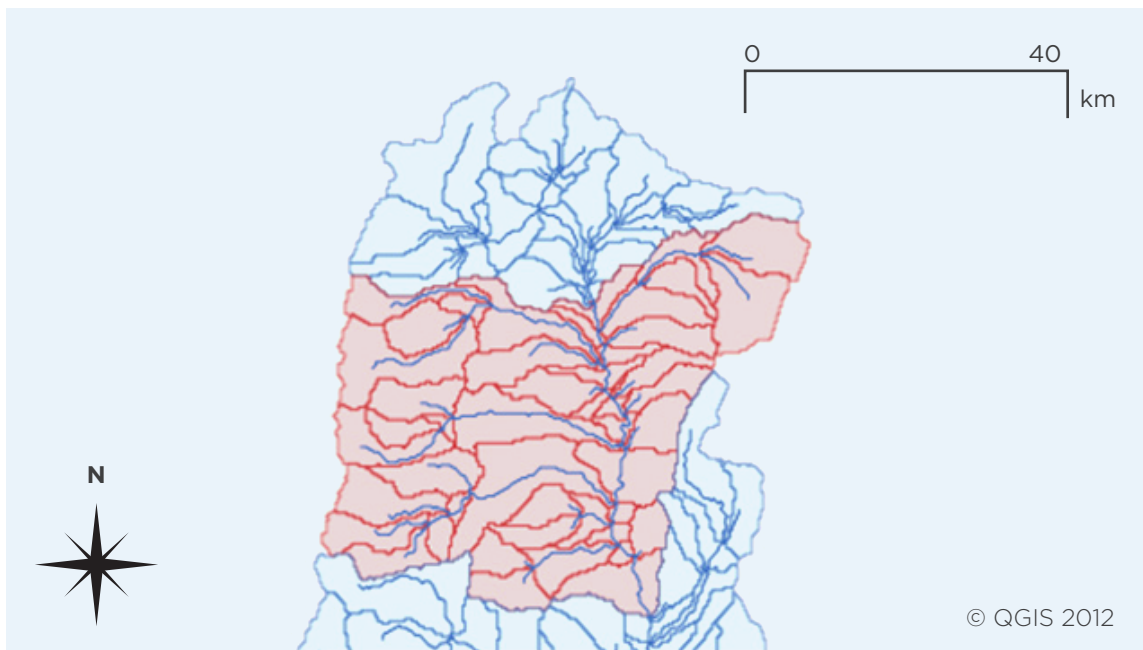
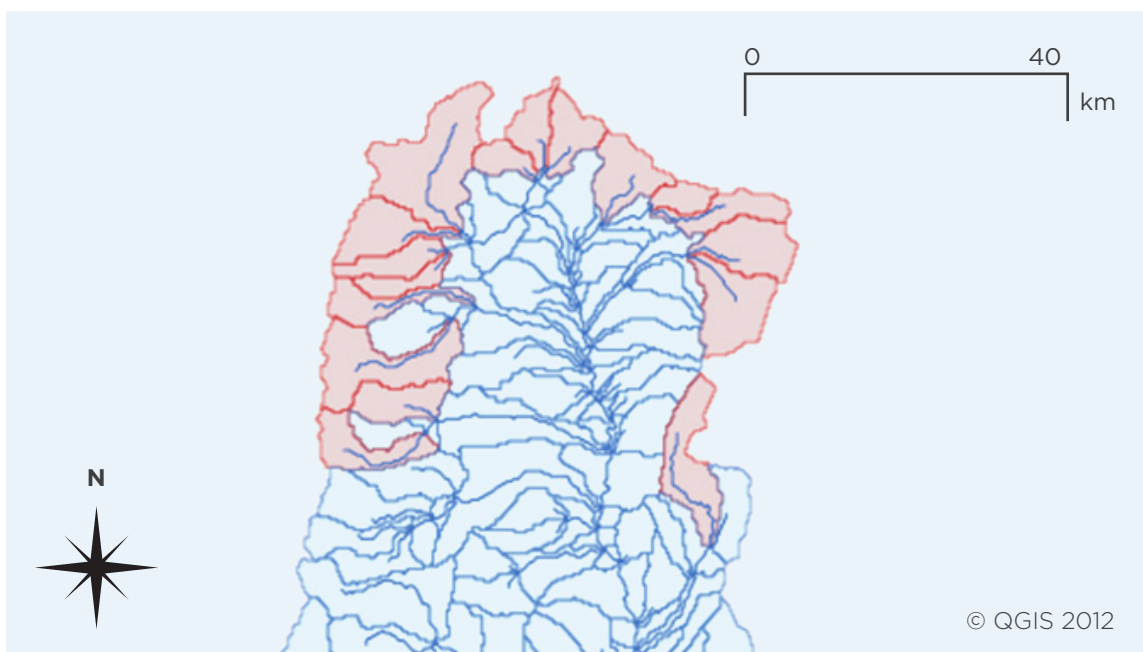
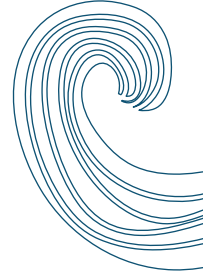


Figure A-8. The Most Upstream Catchments Along the Outline of the Basin Have Been Selected by Holding Down the Control Key and Clicking the Mouse in Each Catchment





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.

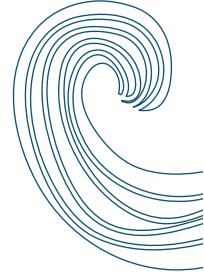
Creating a Subset of AHD

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 stream 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.

Groundwater Data Prep Tool

This tool helps you create a table (.dbf), shapefile (.shp), or.csv file to use as input with your groundwater modeling processes. The outputs are created by joining catchment COMID values onto each point that falls within them. Points not falling within them will have a blank COMID.

Select the “Groundwater Data Prep” option from the AHDTools menu to open the “RTI Analytical Hydrology Dataset Groundwater Data Preparation” menu (Figure A-9).

The groundwater points that you want to attribute and the catchment polygons that you want to attribute the points with should be loaded into QGIS as vector layers before attempting to use the tool. Once the groundwater points and catchments have been loaded as layers you can select them from the appropriate combo box labelled “GW Points Layer” and “AHD Catchments Layer” respectively. The two layers should also be in the same coordinate system, if possible.

After making your selections you can hit the “OK” button to perform the joining of the catchment COMIDs to the points. A dialog window will popup asking where you would like to save the output files and what the base name of the files should be (Figure A-10). After navigating to the location and entering a name hit the “Save” button on the popup dialog window. The application will now perform the join and save the results in the location indicated. The menu’s text window should contain a line saying that “The.csv file has been successfully exported” if everything went well. To avoid problems with locks on the results, they are not automatically loaded into the QGIS Layers list, but can be loaded manually and/or used as input by other groundwater modeling processes. See Figure A-11 for a sample of results. Lastly, press the “Close” button to close the menu.

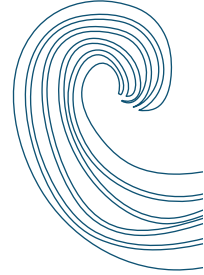


Figure A-9. RTI Analytical Hydrology Dataset Groundwater Data Prep Menu

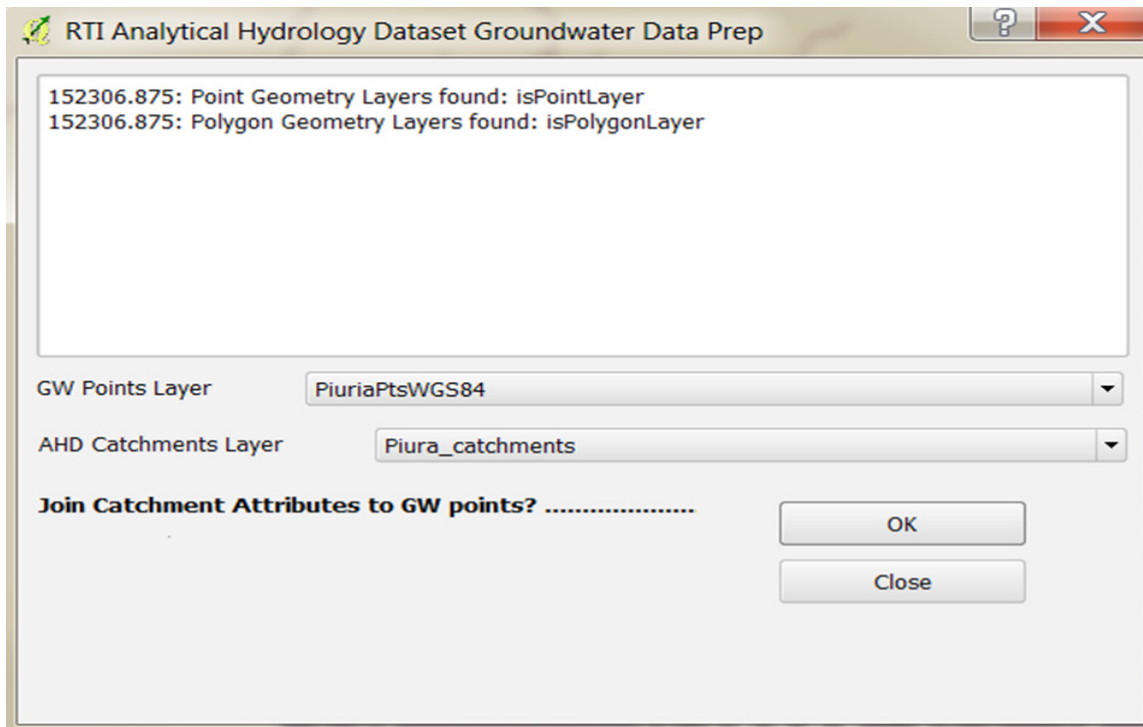
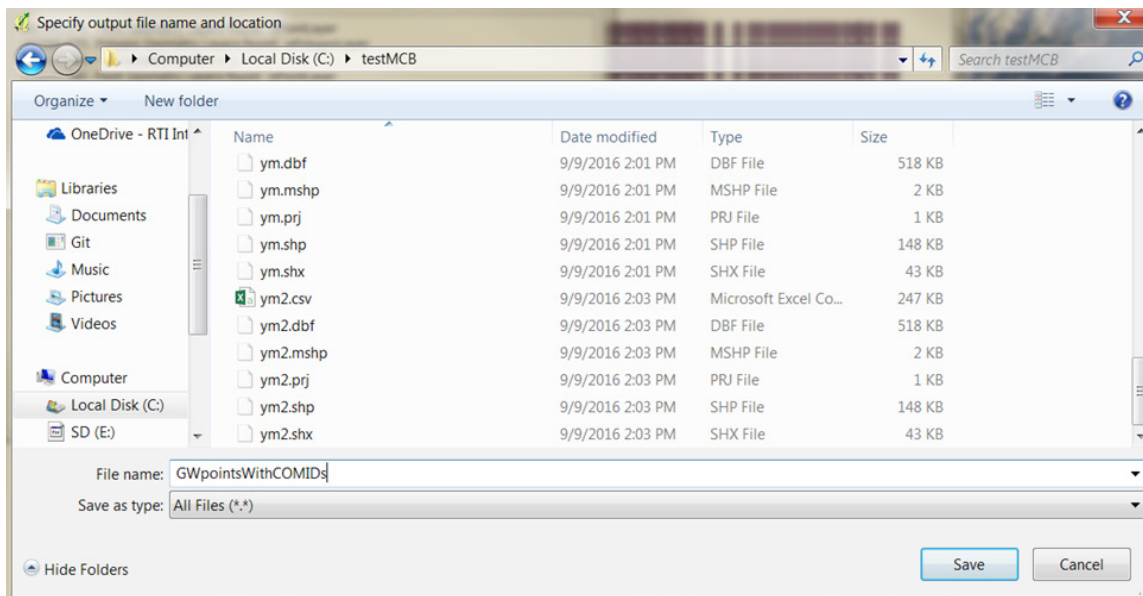


Figure A-10. Groundwater Data Prep Save File Location and Base Name



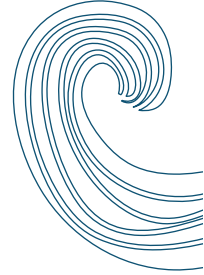
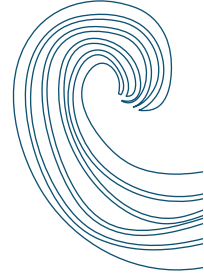


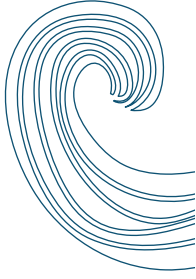
Figure A-11. CSV File (viewed from within Excel) that resulted from the using the Groundwater Data Prep Tool.

LAYER	ROW	COLUMN	TOP	BOTTOM	CELLZ	THICKNES	COMID
1	1	1	65.307	-5.06	30.1235	70.367	305438600
1	1	2	64.626	-1.1011	31.76245	65.7271	305456000
1	1	3	63.013	6.0701	34.54155	56.9429	305456000
1	1	4	62.589	11.878	37.2335	50.711	305456000
1	1	5	67.672	23.594	45.633	44.078	305456000
1	1	6	75.336	38.256	56.796	37.08	305451800
1	1	7	77.703	45.173	61.438	32.53	305451800
1	1	8	80.011	52.814	66.4125	27.197	305451800
1	1	9	80.011	52.814	66.4125	27.197	305451800
1	1	10	82.258	57.767	70.0125	24.491	305464900
1	1	11	83.936	58.081	71.0085	25.855	305464900
1	1	12	85.642	58.978	72.31	26.664	305464900
1	1	13	87.484	57.457	72.4705	30.027	305464900
1	1	14	88.982	56.257	72.6195	32.725	305464900
1	1	15	90.112	55.941	73.0265	34.171	305464900
1	1	16	91.658	54.337	72.9975	37.321	305464900
1	1	17	93.292	51.03	72.161	42.262	305464900
1	1	18	95.213	47.202	71.2075	48.011	305421400
1	1	19	97.284	47.933	72.6085	49.351	305421400
1	1	20	99.243	49.069	74.156	50.174	305421400
1	1	21	102.32	50.463	76.3915	51.857	305421400

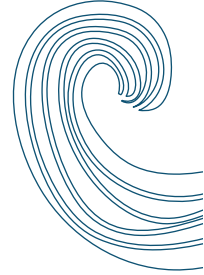


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Appendix B: Hydro-BID Calibration Statistics



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 meters 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

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

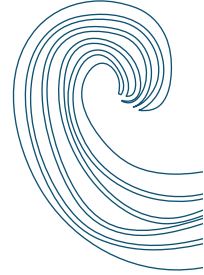
$$S_{(m,y)} = \frac{\sum_{t=1}^{NDAYS} S_t}{NDAYS_{my}} \quad (E.B.2)$$

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

2. Overall volume error (ove)

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

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.B.3), but computes for each year separately.

4. Monthly volume error (mve)

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

5. Correlation -*r*

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

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

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

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

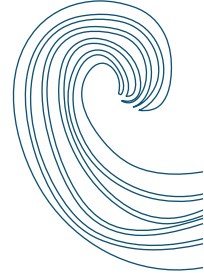
7. Nash-Sutcliffe Efficiency, R²

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

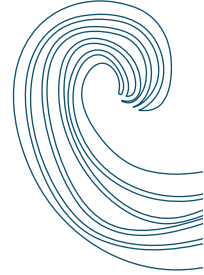
Where μ_o is the mean (average) of observed flow.

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

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



Appendix C: Cutoff Catchments Format



Filename: comid.csv

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

COMID is the unique Catchment Identifier where the cutoff catchment, such as a reservoir, is located.

Example format

COMID	Date	Flow (m ³ /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

