Hydrologic and hydrodynamic modeling of the Amazon: model validation and prospects for stream flow forecasts

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Interesting Challenge

- size of the basin (7,000,000 km²);
- limited data;
- particular hydrological features:
  - climate diversity
  - large rivers
  - backwater effects
  - large wetlands
Integrated Project of Amazon Cooperation and Modernization of Hydrological Monitoring

Projeto Integrado de Cooperação Amazônica e Modernização do Monitoramento Hidrológico

Instituto de Pesquisas Hidráulicas

Instituto Tecnológico da Aeronáutica

Brazilian Water Resources Agency

FINEP
OBJECTIVE

- Development of a hydrological model for the Amazon river basin

- Future: real time hydrological forecasting system.
HYDROLOGICAL MODEL

MGB - IPH (Collischonn, 2001; Paiva, 2009)
Modelo de Grandes Bacias

- Physical based model
- Daily or shorter time step
- Distributed

~ 6000 catchments
MGB-IPH HYDROLOGICAL MODEL

Water Balance

Diagram showing water balance components:
- PC<sub>i</sub>
- ET<sub>ij</sub>
- EI<sub>ij</sub>
- P<sub>ij</sub>
- D<sub>sup</sub><sub>ij</sub>
- D<sub>int</sub><sub>ij</sub>
- D<sub>bas</sub><sub>ij</sub>
- W<sub>m</sub>
- Catchment i
- Downstream catchment
- River channel

Water flows from Catchment i to the downstream catchment via the river channel.
Flow routing modelling

Muskingum Cunge and Hydrodynamic Model

(b) River reaches

MC model
HD model
Hydrodynamic Model

- Hydrodynamic 1D model IPH-IV (Tucci, 1978; Tucci, 2005)

  • Full Saint Venant equations solved with finite difference method
  • Improved Skyline algorithm for river network solution

\[
\frac{\partial Q}{\partial x} + (b + L) \frac{\partial h}{\partial t} = q \quad \frac{\partial Q}{\partial t} + \frac{\partial}{\partial x} \left( \frac{Q^2}{A} \right) + gA \frac{\partial h}{\partial x} = gA(S_0 - S_f)
\]

- Model discretization:
  - Catchments
  - River reaches
  - River cross sections
  - Floodplain units
Hydrodynamic Model

- Flood inundation model:
  
  • Simple Storage model
  • \( v = 0 \)
  • floodplains act only as storage areas
  • horizontal water level
  • river – floodplain lateral exchange:

\[
q_{fl} = \frac{A_{fl}(Z)}{dx} \frac{\partial Z}{\partial t} = L \frac{\partial Z}{\partial t}
\]

- Model discretization:

  - Catchments
  - River reaches
  - River cross sections
  - Floodplain units
Flood inundation model

- **Water depth:**
  - Water level from 1D model
  - Floodplain units
  - DEM
  - 2D flood inundation results
DEM and GIS based algorithms for HD parameter estimation

Cross Section

Geomorphologic equations:

\[ B = a \cdot A_d^b \]

\[ H = a' \cdot A_d^{b'} \]

DEM corrections (vegetation, water):

Water level versus flooded area curve for each floodplain unit

Corrected DEM
DATA

Precipitation and Meteorological Data

- Remote sensed estimates from Tropical Rainfall Measurement Mission
  - Daily rainfall data from TRMM 3B42 algorithm
  - Spatial resolution of 0.25°×0.25°
- Climatic Research Unit – CRU for surface air temperature, atmospheric pressure, solar radiation, moisture and wind speed

Digital Elevation Model

- HydroSHEDS - Hydrological data and maps based on SHuttle Elevation Derivatives at multiple Scales (500 m resolution)

Soil Type and Land Use Data

- A Vegetation map of South America (1 km resolution) from Eva et al. (2002)
- Soil maps:
  - SRIC (World Soil Information) / SOTERLAC (Soil and Terrain database for Latin America and Caribbean) (1:5.000.000)
  - Exploratory Soil Map from RADAMBRASIL (1:1.000.000)
Hydrological Response Units – HRU

HAND - Height Above the Nearest Drainage

Rennó et al. (2008)
MODEL CALIBRATION

- 172 stream gauges
- MOCOM-UA optimization algorithm (Yapo et al., 1998)
MODEL VALIDATION

• Discharge from in situ stream gauge stations
  • ANA Brazil, SENAMHI Peru e Bolivia, HYBAM

• Water levels from in situ stream gauge stations
  • ANA database

• Water levels derived from ENVISAT satellite altimetry data
  • Santos da Silva et al., 2010

• Terrestrial Water Storage from GRACE mission (Tapley et al., 2004a,b)
  • Level-2 land water solutions (RL04)
  • 1 x 1° and monthly time interval
  • GFZ, JPL and CSR solutions
  • 400 and 500 km halfwidth Gaussian filter

• Flood extent from Papa et al. (2010)
  • ~25 x 25 km spatial resolution
  • monthly 1993-2004 time period
Discharge results

- **Japura River**
  - Bad model performance

- **Negro River**
  - Reasonable model performance

![Map of South America with river locations](image)

- Gauge 12845000, $\text{lon} = -69.42^\circ, \text{lat} = -1.40^\circ$
  - $E_N = 0.21, E_{NS} = 0.33, DI = -21\text{ days}, \Delta V = -8\%$

- Gauge 14840000, $\text{lon} = -61.63^\circ, \text{lat} = -1.46^\circ$
  - $E_N = 0.65, E_{NS} = 0.68, DI = 5\text{ days}, \Delta V = -15\%$
Discharge results

- **Purus River**
  - Good model performance

- **Madeira River**
  - Good model performance

![Graph showing discharge results for Purus River and Madeira River with good model performance.](image)
Discharge results

• Tapajós River
  - Good model performance

• Upper Solimões River
  - Good model performance

![Map of South America with river basins and discharge graphs showing model performance for Tapajós and Upper Solimões Rivers.](image)
Discharge results

- **Solimões River at Manacapuru**
  - Good model performance

- **Amazon River at Obidos**
  - Interannual variability
  - Hydrological extremes
  - Good model performance

In the diagram:
- Observed data (blue line)
- Simulated data (red line)

**Solimões River at Manacapuru**
- Gauge 14100000, lon = -60.61°, lat = -3.31°
- ENS = 0.77, ENSlog = 0.76, DI = -10 days, ΔV = -8 %

**Amazon River at Obidos**
- Gauge 17050001, Hybam, lon = -55.51°, lat = -1.92°
- ENS = 0.77, ENSlog = 0.79, DI = -17 days, ΔV = -8 %
Discharge results

- Overall good model performance
- ENS > 0.6 in ~70% of the gauges
- ENS > 0.8 in ~35% of the gauges
- Most of errors are located rivers draining areas outside Brazil such as Peru and Bolivia
- Probably due to precipitation errors
Discharge results

- Overall good model performance
- $\Delta V < 5\%$ in $\approx 50\%$ of the gauges
- $\Delta V < 15\%$ in $\approx 75\%$ of the gauges
- Most of errors are located rivers draining areas outside Brazil such as Peru and Bolivia
- Probably due to precipitation errors
Discharge results

- Overall good model performance
- DI < 5 days in ~70% of the gauges
- DI < 15 days in ~90% of the gauges
Water levels from stream gauge stations

ANA database

Nash and Sutcliffe Index

- Overall good model performance
- Errors in lower amazon (DEM)
- Errors in rivers draining outside Brazil (Discharge errors)
Water levels derived from ENVISAT satellite altimetry

Santos da Silva et al. (2010)

**Nash and Sutcliffe Index**

- Overall good model performance
- Errors in lower Amazon (DEM)
- Errors in rivers draining outside Brazil (Discharge errors)
Nash and Sutcliffe Index

- Overall good model performance
- ENS = 0.93

- Model simulates inter-annual variability including the 2005 drought and the 2009 flood

- Errors in areas draining outside Brazil
Flood inundation results

Central Amazon – Minimum water depth from the 2001/2002 year
Flood inundation results

Central Amazon – Maximum water depth from the 2001/2002 year
Flood inundation extent

Remote Sensing estimates from Papa et al. (2010)

Overall model results are similar to remote sensing estimates

Seasonal variation of inundation extent
Flood inundation extent

Central Amazon:
Reasonable model performance

Bolivian Amazon:
Model misses flood peaks
Flood inundation extent

**Lower Amazon:**
Model misses amplitude of flood extent

\[ ENS = -3.39, R = 0.90, \Delta' = -88\%, BIAS = -30\% \]

![Graph showing flooded area in Lower Amazon with model performance metrics](image)

**Amazon River basin:**
Good model performance

\[ ENS = 0.71, R = 0.92, \Delta' = -26\%, BIAS = -7\% \]

![Graph showing flooded area in Amazon River Basin with model performance metrics](image)

Remote Sensing

- Remote Sensing
- Model
Model Validation - Discussion

Validation showed some model limitations:

- Most of errors in discharge, water level, TWS and inundation extent occurred in areas outside Brazil. We speculate that these are due to the poor quality of TRMM 3b42 rainfall datasets in these areas poorly monitored and/or mountainous.

- Uncertainty in river and floodplain geometry, estimated using geomorphological relations and the SRTM DEM, caused important errors in simulated water levels and inundation extent. Better methods for estimating river and floodplain geometry should still be investigated.
Prospects for stream flow forecasts

On the sources of hydrological prediction uncertainty in the Amazon

Relative importance of *hydrologic initial conditions* and model *meteorological forcings* errors as sources of stream flow forecast *uncertainty*

**Ensemble Stream Flow Prediction (ESP) climate forecast uncertainty**

**versus**

**Reverse Ensemble Stream Flow Prediction (rev-ESP) initial condition uncertainty**

Wood and Lettenmaier (2008)
Prospects for stream flow forecasts

On the sources of hydrological prediction uncertainty in the Amazon

Examples:

Tapajós River at Itaituba

Amazon River at Obidos

Tapajós River

Amazon River

ESP

Rev-ESP
Prospects for stream flow forecasts

On the sources of hydrological prediction uncertainty in the Amazon

*hydrologic initial conditions* are less important than *meteorological forcings* errors after $T$ days

- Uncertainty on initial conditions may play an important role for discharge forecasts even for large lead times ($\sim 1$ to 3 months)

- This suggests that an Ensemble Streamflow Prediction approach (ENS), based on a hydrological model forced with historical meteorological data and using optimal initial conditions, may be feasible for hydrological forecasting

- Development of data assimilation methods is encouraged for reducing model initial conditions uncertainty.
Conclusions

• Results show the good performance of the modeling approach in the Amazon River basin, mainly for discharge results.

• The model was able to reproduce hydrographs in most sites, including large rivers with large flood wave travel times but also small rivers with rapid floods.

• However, validation showed some limitations, mainly related to model input data. We speculate that these are due to:
  
  • Poor quality of TRMM 3b42 rainfall dataset outside Brazil in these areas poorly monitored and/or mountainous
  
  • Uncertainty in river and floodplain geometry, estimated using geomorphological relations and the SRTM DEM
  
  • Uncertainty on initial conditions may play an important role for discharge forecasts even for large lead times (≈ 1 to 3 months)
  
  • Development of data assimilation methods is encouraged for reducing model initial conditions uncertainty.
Gracias
Obrigado
Thank you
Merci