Snow Melt Runoff Modeling

Amit Kumar Dubey
LHD/GHCAG/EPASA
Introduction

- Snowmelt is a primary source of water in the mountainous regions.
- Most of the downstream rivers sustain by the snowmelt runoff.
- The Hydrological budget of Himalayan rivers is dominated by monsoonal rainfall and snowmelt.
- Rivers originating from Himalaya are essential for agriculture and energy generation.

Snow Melt runoff Models

- There are two basic approaches under which most of the models have been developed to simulate the snow hydrology.
  1. Temperature index method
  2. Energy Balance method
## Model Approaches

<table>
<thead>
<tr>
<th>Model Approach</th>
<th>Input Parameters</th>
<th>Output</th>
<th>Remark</th>
</tr>
</thead>
</table>
| **Temperature Index method** | Air Temperature, Precipitation, Snow covered area.  
Rainfall runoff coefficient, Critical Temperature, Temperature lapse rate, Time lag | Daily stream flow, Seasonal volume of runoff     | Does not consider the spatial variability of physical processes for the model input and calibration. It could be applied with limited amount of available observed data set |
| **Energy Balance Method** | Air temperature, Radiation (Shortwave, Longwave), Precipitation, Wind speed, Relative Humidity, Snow surface temperature, Albedo, Snow cover area, cloud cover, Pressure, Elevation. | Snow melt depth, evaporation                      | It requires large amount of input data for model simulations           |
Challenges and Limitations

-Challenges

- Integrated approach to address different hydrological processes within a catchment (e.g., Non snow runoff generation).
- Lumped, Distribute and semi-distributed runoff routing to generate hydrograph at the outlet of the watershed.
- Spatial and temporal scale variability to address short duration events.

-Limitations

- Data intensive.
- Depends on the Accuracy of weather models.
- Implementation over large area requires intensive calibration.
- There is no temperature index which may be applicable in all types of environment and geography. Each temperature index is considered to be applicable to a specific watershed.
# Snow Melt runoff Models

(a) Models Based on Energy Balance Approach

<table>
<thead>
<tr>
<th>Model</th>
<th>Affiliation</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>GOEtop</td>
<td>University of Trento (Italy)</td>
<td>Consists characteristics of both LSMs and flood-forecasting models</td>
</tr>
<tr>
<td>UEB</td>
<td>U. S. Department of Agriculture</td>
<td>Energy balance approach for snow melt depth generation</td>
</tr>
<tr>
<td>DHSVM</td>
<td>University of Washington Hydrology Group</td>
<td>It includes canopy evapo-transpiration, an energy balance model for snow accumulation and melting</td>
</tr>
<tr>
<td>UBCWM</td>
<td>University of British Columbia</td>
<td>Detailed Energy Balance approach to estimate snow melt depth</td>
</tr>
</tbody>
</table>

(b) Models Based on Conceptual / Hybrid Approach

<table>
<thead>
<tr>
<th>Model</th>
<th>Affiliation</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>MIKE SHE</td>
<td>DHI</td>
<td>Distributed Hydrological model includes temperature, radiation and advection melting.</td>
</tr>
<tr>
<td>SRM</td>
<td>USDA</td>
<td>Design to simulate and forecast daily stream flow in mountainous regions</td>
</tr>
<tr>
<td>WaSiM-ETH</td>
<td>ETH, Zurich</td>
<td>Temperature index gridded hydrological catchment model</td>
</tr>
<tr>
<td>SWAT</td>
<td>Texas AM&amp;U</td>
<td>Uses Hydrological response units to estimate runoff from a watershed</td>
</tr>
</tbody>
</table>

(c) Model Schemes presented on GCM and Weather forecasting model

<table>
<thead>
<tr>
<th>Model</th>
<th>Affiliation</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Noah LSM</td>
<td>NOAA</td>
<td>Land surface model coupled to weather forecast models</td>
</tr>
<tr>
<td>VIC</td>
<td>University of Washington</td>
<td>As a semi-distributed macroscale hydrological model, Uses a separate routing model</td>
</tr>
</tbody>
</table>
Data for snowmelt modeling

- **Satellite Data**
  - Precipitation (INSAT 3D, TRMM)
  - Digital Elevation Model (SRTM, CARTOSAT)
  - Snow Cover (INSAT-3D, MODIS)
  - Land use/Land cover (MODIS)

- **Model Data (WRF output 5 KM)**
  - Air Temperature (2 m)
  - Land surface temperature
  - Wind speed (10 m)
  - Downward shortwave radiation
  - Downward longwave radiation
  - Relative Humidity (2 m)
  - Pressure
WRF Simulated Input Parameters (5 km)

- Air Temperature (°C)
- Wind Speed (m/sec)
- Shortwave Down Radiation (W/m²)
- Surface skin Temperature (K)
- Relative Humidity (%)
- Longwave Down Radiation (W/m²)

WRF simulated outputs on 6th May 2017, 11:30 AM over India
Hydrological modeling - Methodology

Infiltration estimation (Green-Ampt model)
- Soil Moisture
  - Surface runoff Depth

PET estimation (Priestley Taylor method)
- AET estimation (Priestley Taylor method)
  - Snow Melt Depth

Energy and Mass Balance Over snow Cover Regions

WRF Simulated Meteorological parameters
- Cloud cover
  - Wind speed (10 m above surface)
  - Snow Surface and Air Temperature (2m above surface)
  - Incoming Shortwave and Long wave Radiation

Precipitation
- Threshold Temperature
  - Rain
  - Snow

Snow Cover Map

Digital Elevation Model
- Watershed Delineation
- Flow Direction/Accumulation matrix
  - Flow Routing
    - Discharge Hydrograph
Energy Budget over Snowpack

Fig. Snowpack Heat and mass balance (Source: Assaf, H., 2007)

\[
\frac{\partial U_i}{\partial t} = Q_s + Q_l + Q_h + Q_e + Q_a + Q_g - Q_m
\]

Snow Melt depth Estimation

\[ M_p = \frac{Q_m}{H_{fw} \rho_w B} \]

- \( M_p \) is the volume of potential snowmelt in \( mm/s \) (1 mm is equivalent to a volume of 1 mm over an area of \( m^2 \), equivalent to 1 liter);
- \( Q_m \) is the energy available for snowmelt as defined in equation 1 in \( \frac{J}{m^2} \);
- \( H_{fw} \) is the heat fusion of ice equal to 334.9 \( \frac{J}{g} \) (Joule/gram);
- \( \rho_w \) is water density equal to 1000 \( \frac{kg}{m^3} \); and
- \( B \) is the thermal quality of the snow defined as the ratio of heat required to melt a unit mass of snow to that of ice at 0 \( ^\circ \)C, which ranges in value from 0.95 to 0.97 for a melting snowpack (USACE (1998)).
Soil moisture estimation - Green-Ampt infiltration model

Assumptions

- Homogenous soil profile
- Uniformly antecedent moisture distributed in the soil profile
- The soil above the wetting front is considered to be completely saturate.

\[ F(t) = \psi \Delta \theta \ln \left( 1 + \frac{F(t)}{\psi \Delta \theta} \right) = Kt \]

\[ f = K \left[ \frac{\psi \Delta \theta + F}{F} \right] \]

- \( F(t) \) – Cumulative infiltration in cm
- \( f \) - Infiltration rate in cm/hr
- \( K \) – Hydraulic conductivity in cm/hr
- \( \psi \) - Wetting front soil suction head cm
- \( \Delta \theta = (1 - S_e) \theta_e \)
Actual Evapotranspiration – Model computation

- Model computes **Potential ET** using Priestley-Taylor approach:

\[
PET = \alpha_{pt} \left[ \frac{\Delta}{\Delta + \gamma} \cdot \frac{R - G}{\lambda} \right]
\]

Where, \( \alpha_{pt} \) is the Priestley-Taylor constant,
\( \Delta \) is slope of saturation vapour pressure,
\( \gamma \) is psychrometric constant,
\( R \) is net radiation at surface,
\( G \) is ground heat flux and
\( \lambda \) is latent heat of vaporization of water.

- **Actual ET** is calculated as

\[
AET = \begin{cases} 
PET; Prcp > PET \\
\frac{\theta - \theta_{wp}}{\theta_{fc} - \theta_{wp}} \cdot PET; Prcp < PET 
\end{cases}
\]

Where, \( \theta \) is present soil moisture,
\( \theta_{wp} \) is wilting point,
\( \theta_{fc} \) is field capacity and
\( Prcp \) is Precipitation.
# Flow Routing

Flow Direction, Flow Line Generation and Accumulation

<table>
<thead>
<tr>
<th>Routing Scheme</th>
<th>Flow Routing</th>
</tr>
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<tbody>
<tr>
<td></td>
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</tbody>
</table>

Number represents upstream cell count
Channel and Overland Cell Identification

Routing Scheme

OUTLET

Grid number

Threshold Value is 3 (for channel cell)

Overland cells

Channel cells

Non-contributing cells
# Flow Estimation

## Flow Estimation Diagram

![Flow Estimation Diagram]

## Flow at Outlet on 01/09/2010: Q4+ Q5+ Q6+Q7

## Flow at Outlet on 02/09/2010: Q2+Q3

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## Flow at Outlet

<table>
<thead>
<tr>
<th>Cell id</th>
<th>Travel time (h)</th>
<th>Q</th>
<th>Event Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>18</td>
<td>52</td>
<td>Q1</td>
<td>31/08/2010</td>
</tr>
<tr>
<td>15</td>
<td>48</td>
<td>Q2</td>
<td>31/08/2010</td>
</tr>
<tr>
<td>14</td>
<td>36</td>
<td>Q3</td>
<td>31/08/2010</td>
</tr>
<tr>
<td>10</td>
<td>10</td>
<td>Q4</td>
<td>31/08/2010</td>
</tr>
<tr>
<td>9</td>
<td>16</td>
<td>Q5</td>
<td>31/08/2010</td>
</tr>
<tr>
<td>8</td>
<td>24</td>
<td>Q6</td>
<td>31/08/2015</td>
</tr>
<tr>
<td>5</td>
<td>4</td>
<td>Q7</td>
<td>31/08/2015</td>
</tr>
</tbody>
</table>
Streamflow Estimation at upstream Himalayan Catchments
Streamflow Estimation in upstream catchments of the Himalayan region
(Study area, showing topography)
Accumulated Precipitation over Upstream catchments of the Himalayan region for the Year 2014 (Mar, Apr, May, Jun, Jul)
Average Net Shortwave flux over Upstream catchments of the Himalayan region for the Year 2014 (Mar, Apr, May, Jun, Jul)
Average Net Longwave flux over Upstream catchments of the Himalayan region for the Year 2014 (Mar, Apr, May, Jun, Jul)
Average Sensible heat flux over Upstream catchments of the Himalayan region for the Year 2014 (Mar, Apr, May, Jun, Jul)
Averaged Latent heat flux over Upstream catchments of the Himalayan region for the Year 2014 (Mar, Apr, May, Jun, Jul)
Averaged Net heat flux over Upstream catchments of the Himalayan region for the Year 2014 (Mar, Apr, May, Jun, Jul)
Averaged PET over Upstream catchments of the Himalayan region for the Year 2014 (Mar, Apr, May, Jun, Jul)
Average AET over Upstream catchments of the Himalayan region for the Year 2014 (Mar, Apr, May, Jun, Jul)
Discharge comparison for major catchments of Himalaya
Snow Cover variation over the Upstream catchments of Himalayan region

<table>
<thead>
<tr>
<th>Basin</th>
<th>Area (sq. km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Indus</td>
<td>3,13,584</td>
</tr>
<tr>
<td>Sutlej</td>
<td>73,898</td>
</tr>
<tr>
<td>Brahmaputra</td>
<td>3,37,598</td>
</tr>
</tbody>
</table>

Basin Area (sq. km)

- Indus: 3,13,584
- Sutlej: 73,898
- Brahmaputra: 3,37,598
Sutlej river upstream catchment
Monthly Discharge comparison

I. Sutlej basin
Indus river upstream catchment
Brahmaputra river upstream catchment
Summary

• On an annual timescale snowmelt provides 15 to 60 % of discharge in the western Himalaya (Indus to Sutlej).

• Indus discharge has a significant snowmelt component 65.7 % on annual discharge.

• Sutlej river also receive high contribution (57.1 %) of snow melt on annual discharge.

• Snow melt contribute 34.3 % and 22.4 % on annual discharge of Brahmaputra and Ganges river, respectively.

• In the Eastern Himalaya the annual discharge (>80 %) is primarily derived from rainfall (May – October) for the rivers like, Dibang, Subansiri and Manas.
WRF Hydro: Coupled weather Hydrology model

WRF-hydro

- WRF: Weather Research and Forecasting Model
- NDHMS: the NCAR Distributed hydrological Modeling System (Noah based)
- WRF-hydro: NDHMS coupling with WRF
Methodology - WRF Modeling Architecture
WRF Hydro setup over Beas river
WRF-Hydro Domain design

- ERA-Interim 6 hourly
- 27km: 125x125
- 9km: 100x100
- 3km: 118x118
- Routing subgrid: 300m
WRF-Hydro

1. Multi-scale aggregation/disaggregation
2. High resolution hydro terrain grids

Noah LSM grid (3 km)
Routing grid (300 m)
Routing channels (300 m)
Experiments design

<table>
<thead>
<tr>
<th>Name</th>
<th>Physical MP schemes</th>
</tr>
</thead>
<tbody>
<tr>
<td>CU (1)</td>
<td>Kain–Fritsch Scheme*</td>
</tr>
<tr>
<td>MP (3)</td>
<td>simple 3-class scheme</td>
</tr>
<tr>
<td>MP (8)</td>
<td>Thompson Scheme</td>
</tr>
<tr>
<td>LS (1)</td>
<td>Unified Noah Land Surface Model</td>
</tr>
<tr>
<td>PBL (1)</td>
<td>Yonsei University scheme</td>
</tr>
<tr>
<td>LW (1)</td>
<td>RRTM scheme</td>
</tr>
<tr>
<td>SW (1)</td>
<td>Dudhia scheme</td>
</tr>
<tr>
<td>Boundary</td>
<td>ECMWF ERA-Interim reanalysis data</td>
</tr>
</tbody>
</table>

- A standard set-up was used with 40 vertical layers
- The model time-step was around 8 s in the small domain
- The simulation was run from 1996 to 2001 and the first year of 1996 is for initialization.
- The sea-surface temperature (SST) was updated (sst_skin=1) by forcing data.
Land surface Processes in WRF Model

Figure 1. NOAH Land surface processes (Source: Chen and Dudhia, 2002)
Hydrologically-enhanced Land Surface Models
(Gochis and Chen, 2003, NCAR Tech Note)

Snow melting
Single Column

Run off
Land Surface Routing
Explicit diffusive wave overland flow

Channel Routing

1-D Land Surface Models (e.g. ‘Noah’)

Base flow
Subsurface Routing

Three major components for river forecasting:
Snow melting, base flow and run off
• Study Area (Parbati Basin)

• Simulation Domain
  ◦ Simulation period – 01-02 July 2009 (48 hr)
  ◦ Spatial resolution – 2 Km
  ◦ Temporal resolution – 6 hr
  ◦ Watershed Area – 2068 Km²
Watershed Topography Variation with Drainage network

DEM (m)

Parbati Basin

Legend

SourceDEM

Value
High : 6899
Low : 202
Fig. 10 Topography variations over Parbati basin (ASTER- 30 m)
Snow Cover (%)  

Legend

Snow Cover (%)  

Value

High : 100

Low : 0

Albedo (%)

Fig. 11 Variation of Snow Cover and Albedo on 02 July 2009 at 12:00 IST
Fig. 12 Variation of Air temperature with wind direction and Surface temperature on 02 July 2009 at 12:00 IST
Fig. 13  Wind Speed (m/sec) at 10 m and relative humidity at 2 m above the surface on 02 July 2009 at 12:00 IST
Future Direction with Indian satellite Input

- Assimilation of scatterometer (SCATSAT-1) data into the Hydrological model for surface runoff generation.

- Use of Insolation from Kalpana data into the Hydrological model.

- To explore the potential of SARAL/Altika or different altimeters for model calibration and validation at downstream locations of the catchments.

- Land use/Land cover from AWIFS.

- Streamflow forecasting using projected model input parameters.
USGS Flood Inundation Mapping program

Inundation maps translate flood data into operational maps that communicate risk and the consequences of current and forecasted flooding.
FLOODPATH – Real time flood forecasting system

https://wa.water.usgs.gov/projects/floodpath/maps.htm