STREAM FLOW (SNOWMELT RUNOFF) MODELLING IN HIMALAYAN BASINS

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Himalayan Water Resources

- About 35% of the geographical area of India is covered by mountains and 58% of this is accounted for by the mighty Himalayas in which more than 5000 glaciers covering about 38000 km² area.

- There are 22 major river systems with about 1 million km² catchment area lying in the Himalayas, with snow and glacier melt runoff of more than 50%.

- The seasonal snow and glacier melt coming from the Himalayan Rivers is a dependable source of water for irrigation, hydroelectric power and drinking water supply.

- The hydropower generation contributes about 26% of total installed capacity in India in which Himalayan river systems contribute 78% of the total Indian hydropower potential.

- Snow melt modelling is a crucial element to predict runoff from snow-covered or glacierised areas, as well as to assess changes in the cryosphere associated with climate change.
The Himalayan System

**Western Disturbances**
- Nov. – March/April

**Terai**
- 900-1500m
- <300m

**Siwalik**
- 1500- 3500m

**Outer Himalaya**
- 3600-4600m
- 4000m

**Lesser Himalaya**
- 900-1500m

**Greater Himalaya**
- > 4600m

**Tibetan Plateau**
- 4000m

**Glaciers**
- 10%

**Winter snow cover**
- 35-50%

**Maximum monsoon precipitation**
- at 1500 – 3000 m asl

**SW Monsoon**
- June – Sep
Basins of all major Himalayan rivers have combination of both glacial and nonglacial watersheds.

- **Glacial watershed** is characterized as
  - High energy and characteristic landforms (Hewitt, 1972)
  - High elevation and steep slope
  - Rocky terrain
  - Presence of ice and snow
  - Less biotic activities

- **Non-glacial (spring fed) watersheds** generally have
  - Lower elevations and gentle slopes
  - Medium to good soil depth
  - Intensive biotic activities
STREAM FLOW MODELLING (SNOWMELT RUNOFF)

Main steps in modelling are as follows:

Division of Basin Into Elevation Bands

Processing of Meteorological Data
  • Temperature Distribution
  • Precipitation Distribution

Variability of Snow Covered Area

Form of Precipitation

Melt due to rain

Degree Day Factor for Snow and Ice

Routing of Surface and Sub Surface Flow
Problems in remote sensing of snow in visible band

- Cloud and snow have same reflectance
- Mountain shadow behaves as non-snow area

Snow Mapping methods

- Training sites supervised classification (SC)
- Reflectance Statistics
- Normalized Difference Snow Index (NDSI)

\[
\text{NDSI} = \frac{\text{Visible Band} - \text{SWIR Band}}{\text{Visible Band} + \text{SWIR Band}}
\]

(Snow exhibits high reflectance in visible band and strong absorption in SWIR band
Cloud on the other hand shows uniform reflectance due to non-selective scattering)

Snow Cover Mapping from LANDSAT, IRS, NOAA and MODIS data have been carried out for all the basins.
<table>
<thead>
<tr>
<th>Basin</th>
<th>Site</th>
<th>Total Area (km²)</th>
<th>Max. SCA (km²)</th>
<th>Min. SCA (km²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chenab Basin</td>
<td>Akhnoor</td>
<td>22,200</td>
<td>15,590 (70%)</td>
<td>5,400 (24%)</td>
</tr>
<tr>
<td>Satluj Basin</td>
<td>Bhakra Dam</td>
<td>22,275</td>
<td>14,498 (65%)</td>
<td>4,528 (20%)</td>
</tr>
<tr>
<td>(Indian part)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Beas Basin</td>
<td>Pandoh Dam</td>
<td>5,278</td>
<td>2,700 (51%)</td>
<td>780 (14%)</td>
</tr>
<tr>
<td>Ganga Basin</td>
<td>Devprayag</td>
<td>19,700</td>
<td>9,080 (46%)</td>
<td>3,800 (19%)</td>
</tr>
</tbody>
</table>
BEAS BASIN up to PANDOH DAM

AREA = 5728 km²
ALTITUDE = 600 to 5400 meter
DEM of Beas Basin
<table>
<thead>
<tr>
<th>Zones</th>
<th>Elevation range (m)</th>
<th>Area (km²)</th>
<th>Percentage</th>
<th>Raingauge station</th>
<th>Temperature station</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>600-1200</td>
<td>77.34</td>
<td>1.46</td>
<td>Pandoh</td>
<td>Pandoh</td>
</tr>
<tr>
<td>2</td>
<td>1200-1800</td>
<td>467.56</td>
<td>8.84</td>
<td>Largi</td>
<td>Bhunter</td>
</tr>
<tr>
<td>3</td>
<td>1800-2400</td>
<td>823.90</td>
<td>15.57</td>
<td>Manali</td>
<td>Largi</td>
</tr>
<tr>
<td>4</td>
<td>2400-3000</td>
<td>954.12</td>
<td>18.03</td>
<td>Manali</td>
<td>Manali</td>
</tr>
<tr>
<td>5</td>
<td>3000-3600</td>
<td>713.2</td>
<td>13.47</td>
<td>Manali</td>
<td>Manali</td>
</tr>
<tr>
<td>6</td>
<td>3600-4200</td>
<td>659.63</td>
<td>12.46</td>
<td>Sainj</td>
<td>Manali</td>
</tr>
<tr>
<td>7</td>
<td>4200-4800</td>
<td>811.53</td>
<td>15.33</td>
<td>Sainj</td>
<td>Manali</td>
</tr>
<tr>
<td>8</td>
<td>4800-5400</td>
<td>691.51</td>
<td>13.06</td>
<td>Sainj</td>
<td>Manali</td>
</tr>
<tr>
<td>9</td>
<td>&gt;5400</td>
<td>94.10</td>
<td>1.78</td>
<td>Sainj</td>
<td>Manali</td>
</tr>
</tbody>
</table>
SNOW COVER AREA (MODIS)

January
February
March
April
May
June
July
August
September
October
November
December
## SNOW COVER AREA (%)

<table>
<thead>
<tr>
<th>YEAR</th>
<th>2000</th>
<th>2001</th>
<th>2002</th>
<th>2003</th>
<th>2004</th>
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<tr>
<td>March</td>
<td>74.85</td>
<td>65.11</td>
<td>73.65</td>
<td>67.75</td>
<td>71.13</td>
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<tr>
<td>March</td>
<td>88.47</td>
<td>70.09</td>
<td>87.62</td>
<td>71.61</td>
<td>63.63</td>
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<tr>
<td>March</td>
<td>75.52</td>
<td>54.58</td>
<td>68.44</td>
<td>61.35</td>
<td>55.43</td>
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<tr>
<td>March</td>
<td>58.23</td>
<td>64.62</td>
<td>66.33</td>
<td>47.93</td>
<td>48.28</td>
</tr>
<tr>
<td>April</td>
<td>51.23</td>
<td>63.63</td>
<td>48.23</td>
<td>66.69</td>
<td>42.47</td>
</tr>
<tr>
<td>April</td>
<td>43.29</td>
<td>62.68</td>
<td>59.45</td>
<td>55.78</td>
<td>39.98</td>
</tr>
<tr>
<td>April</td>
<td>43.67</td>
<td>48.31</td>
<td>51.11</td>
<td>50.92</td>
<td>36.76</td>
</tr>
<tr>
<td>April</td>
<td>41.42</td>
<td>51.76</td>
<td>45.47</td>
<td>49.40</td>
<td>39.33</td>
</tr>
<tr>
<td>May</td>
<td>36.76</td>
<td>46.56</td>
<td>56.81</td>
<td>39.03</td>
<td>45.16</td>
</tr>
<tr>
<td>May</td>
<td>31.53</td>
<td>43.06</td>
<td>45.29</td>
<td>39.20</td>
<td>54.70</td>
</tr>
<tr>
<td>May</td>
<td>26.90</td>
<td>37.98</td>
<td>38.90</td>
<td>35.45</td>
<td>35.51</td>
</tr>
<tr>
<td>June</td>
<td>35.19</td>
<td>34.99</td>
<td>35.59</td>
<td>37.11</td>
<td>37.16</td>
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<tr>
<td>June</td>
<td>24.39</td>
<td>31.19</td>
<td>29.12</td>
<td>30.23</td>
<td>31.80</td>
</tr>
<tr>
<td>June</td>
<td>18.02</td>
<td>25.10</td>
<td>28.70</td>
<td>19.21</td>
<td>37.11</td>
</tr>
<tr>
<td>June</td>
<td>12.46</td>
<td>22.21</td>
<td>21.42</td>
<td>22.16</td>
<td>21.47</td>
</tr>
<tr>
<td>July</td>
<td>13.62</td>
<td>12.66</td>
<td>27.53</td>
<td>11.43</td>
<td>21.84</td>
</tr>
<tr>
<td>July</td>
<td>9.67</td>
<td>9.05</td>
<td>11.91</td>
<td>10.77</td>
<td>17.81</td>
</tr>
<tr>
<td>July</td>
<td>10.85</td>
<td>11.04</td>
<td>10.68</td>
<td>10.35</td>
<td>9.01</td>
</tr>
<tr>
<td>August</td>
<td>10.14</td>
<td>8.45</td>
<td>14.00</td>
<td>8.96</td>
<td>11.56</td>
</tr>
<tr>
<td>August</td>
<td>11.42</td>
<td>9.49</td>
<td>8.00</td>
<td>9.34</td>
<td>13.93</td>
</tr>
<tr>
<td>August</td>
<td>9.62</td>
<td>10.35</td>
<td>9.16</td>
<td>9.00</td>
<td>10.92</td>
</tr>
<tr>
<td>August</td>
<td>12.00</td>
<td>9.48</td>
<td>14.84</td>
<td>10.71</td>
<td>9.39</td>
</tr>
<tr>
<td>September</td>
<td>12.37</td>
<td>11.79</td>
<td>10.34</td>
<td>11.12</td>
<td>11.37</td>
</tr>
<tr>
<td>September</td>
<td>12.06</td>
<td>16.01</td>
<td>19.55</td>
<td>12.00</td>
<td>10.33</td>
</tr>
<tr>
<td>September</td>
<td>23.07</td>
<td>20.74</td>
<td>19.04</td>
<td>13.05</td>
<td>12.84</td>
</tr>
</tbody>
</table>
SNOW COVER DEPLETION CURVES

SCA % vs. Weeks

- 2000
- 2001
- 2002
- 2003

Weeks:
- 2000-03-05-12
- 2000-03-13-20
- 2000-03-21-28
- 2000-03-29-04-05
- 2000-04-06-13
- 2000-04-14-21
- 2000-04-22-29
- 2000-04-30-05-07
- 2000-05-08-15
- 2000-05-16-23
- 2000-05-24-31
- 2000-06-01-08
- 2000-06-09-16
- 2000-06-17-24
- 2000-06-25-07-02
- 2000-07-03-10
- 2000-07-19-26
- 2000-07-27-08-02
- 2000-08-04-05
- 2000-08-12-20
- 2000-08-09-09-04
- 2000-09-05-12
- 2000-09-13-20
- 2000-09-21-28
- 2000-09-29-10-06
Snow cover area maps were prepared for the years 2001-2005 using satellite data.

A relationship has been developed between cumulative temperature and snow cover area.

Using this relationship snow cover area for the years 1990-2000 have been prepared.

Snow cover depletion curves for these years have been generated.
Land Surface Temperature (LST)

In this study, LST maps be used to determine TLR for the Beas river basin which will be inputs in snowmelt runoff modeling.

• LST generally defined as the Skin temperature of ground.

• LST data is derived from satellite data are continuous datasets with better spatial and temporal resolution.

• Estimated from satellite data are the energy thermal sensors received in 10.5-12.5 µm wavelength region emitted by land surface.

• It depends on latitude of the location and surface properties, specially surface albedo and specific heat of the surface.
MODIS LST Database for Beas Basin

The MODIS LST products are archived in Hierarchical Data Format - Earth Observing System (HDF-EOS) format files.

MODIS/Terra Land Surface Temperature data - produced using the split window algorithm developed by Wan and Dozier (1996).

Temperatures are extracted in Kelvin with a view-angle dependent algorithm applied to direct observations.

The LST algorithm uses MODIS data in bands 31 and 32 in the split-window (at 11 and 12 microns, respectively).

<table>
<thead>
<tr>
<th>Earth Science Data Type (ESDT)</th>
<th>Spatial Resolution</th>
<th>Temporal Resolution</th>
<th>Period</th>
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<tbody>
<tr>
<td>MOD11A2</td>
<td>1km (actual 0.927km)</td>
<td>eight days</td>
<td>2000 to 2009</td>
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</table>
MODIS LST Maps for Beas basin

<table>
<thead>
<tr>
<th>Temperature</th>
<th>Max</th>
<th>Min</th>
</tr>
</thead>
<tbody>
<tr>
<td>AUGUST</td>
<td>32.06</td>
<td>-1.18</td>
</tr>
<tr>
<td>SEPTEMBER</td>
<td>32.6</td>
<td>-3.22</td>
</tr>
<tr>
<td>OCTOBER</td>
<td>28.24</td>
<td>-5.1</td>
</tr>
<tr>
<td>NOVEMBER</td>
<td>19.34</td>
<td>-22.76</td>
</tr>
</tbody>
</table>

Temperature Range

August 2000

September 2000

October 2000

November 2000
Scatter plots showing the relationship between Elevation and MODIS LST

- February 2000: TLR = 0.7
- August 2000: TLR = 0.6
- June 2000: TLR = 0.3
The model developed was calibrated for the study basin using data of 3 years (2002-2005).

After calibration of the model, the model was used to simulate daily stream flow using independent data of 12 years (1990-1993, 1993-1996, 1996-1999 and 1999-2002).

The different components obtained after simulation are:
- Total stream flow
- Snowmelt runoff
- Rainfall runoff
- Base flow
Calibration result of stream flow for 2002-2005

- Observed runoff
- Computed runoff
- Runoff due to rainfall
- Runoff due to snowmelt
- Runoff due to base flow
Validation result for 1990-1993

- Observed runoff
- Computed runoff
- Runoff due to rainfall
- Runoff due to snowmelt
- Runoff due to base flow

Days (Oct. 1990-Sept. 1993) vs. Runoff (cumec)
Validation result for 1993-1996

[Graph showing observed runoff, computed runoff, runoff due to rainfall, runoff due to snowmelt, and runoff due to base flow.]
Location of the study area and meteorological stations in the Satluj basin

- Jan 11, 2004
- Feb 02, 2004
- Mar 26, 2004
- May 02, 2004
- Jul 08, 2004
- Aug 03, 2004
- Sep 19, 2004
- Oct 16, 2004
- Nov 01, 2004

Satluj Basin
Channel-2
Channel-1
Channel-1

<table>
<thead>
<tr>
<th>Date Range</th>
<th>Image Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jan 17-24, 2004</td>
<td></td>
</tr>
<tr>
<td>Feb 10-17, 2004</td>
<td></td>
</tr>
<tr>
<td>Mar 05-12, 2004</td>
<td></td>
</tr>
<tr>
<td>Apr 14-21, 2004</td>
<td></td>
</tr>
<tr>
<td>May 16-23, 2004</td>
<td></td>
</tr>
<tr>
<td>Jun 09-16, 2004</td>
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</tr>
<tr>
<td>Jun 11-18, 2004</td>
<td></td>
</tr>
<tr>
<td>Aug 04-05, 2004</td>
<td></td>
</tr>
<tr>
<td>Sep 05-12, 2004</td>
<td></td>
</tr>
<tr>
<td>Oct 15-22, 2004</td>
<td></td>
</tr>
<tr>
<td>Nov 09-15, 2004</td>
<td></td>
</tr>
<tr>
<td>Dec 10-17, 2004</td>
<td></td>
</tr>
</tbody>
</table>

Legend:
- Red: Satluj Basin
- Green: Land Cover
- Blue: Water Body/Lake
- Pink: Cloud Cover
- White: Snow Ice/Glacier Ice
The basin is divided into 10 elevation bands with an altitude difference of 600 m.

About 55% of the area lies between 3600 to 5400 m.
Seasonal Lapse Rate estimation from MODIS LST maps

(1) Jan 01-08, 2005
Jan 0.66
y = -0.0067x + 17.829
R² = 0.8839

(2) Feb 10-17, 2005
Feb 0.67
y = -0.0069x + 21.098
R² = 0.9019

(3) Mar 14-22, 2003
Mar 0.66
y = -0.0067x + 27.975
R² = 0.9112

(4) Apr 15-23, 2003
Apr 0.69
y = -0.0069x + 35.468
R² = 0.8823

(5) May 09-16, 2005
May 0.71
y = -0.0071x + 35.659
R² = 0.8835

(6) Jun 10-17, 2005
June 0.72
y = -0.0072x + 41.14
R² = 0.8282

(7) Jul 04-11, 2004
July 0.56
y = -0.0056x + 37.225
R² = 0.7737

(8) Aug 12-19, 2002
Aug 0.55
y = -0.0055x + 39.465
R² = 0.7219

(9) Sep 06-13, 2004
Sept 0.53
y = -0.0053x + 41.397
R² = 0.8472

(10) Oct 12-19, 2003
Oct 0.60
y = -0.006x + 28.569
R² = 0.867

(11) Nov 09-16, 2002
Nov 0.65
y = -0.0065x + 19.317
R² = 0.832

(12) Dec 11-18, 2004
Dec 0.67
y = -0.0067x + 19.057
R² = 0.8702

(the slope of the equation is the temperature lapse rate)

Fixed TLR (0.65 °C/100 m)

2002-2003
R²=0.86

Seasonally varying TLR

2002-2003
R²=0.92

Discharge in Cumec

Time

November, December, January, February, March, April, May, June, July, August, September, October

Observed discharge | Estimated discharge | Rainfall | Snow melt | Base flow
Simulation of Runoff (2004-2005)

Fixed TLR (0.65 °C/100 m)

2004-2005
$R^2=0.82$

Seasonally varying TLR

2004-2005
$R^2=0.84$
Arc SWAT

SWAT stands for Soil and Water Assessment Tool

physically based, spatially distributed, continuous model - daily time step

Allows a basin to be subdivided into sub-basins or W/S

Each sub-basin are further grouped into hydrologic response units (HRUs) based on land use and type of soil.

ArcSWAT requires input data on weather, soil properties, topography, vegetation, & land management practices

ArcSWAT allows data input via GIS

Model outputs all water balance components (surface runoff, evaporation, lateral flow, recharge, percolation, sediment yield, etc.) at each w/s at daily, monthly or annual time steps.
MODEL INPUT

- GIS input files needed for the SWAT model include:
  - the digital elevation model (DEM),
  - land cover, and
  - soil layers

- The DEM can be utilized by ArcSWAT to delineate basin and subbasin boundaries, calculate subbasin average slopes and delineate the stream network.

- The land use, soil and Slope layers are used to create and define Hydrological response units (HRU’s).
METROLOGICAL DATA

The weather variables for driving the hydrological balance are

– precipitation,
– air temperature,
– solar radiation,
– wind speed and
– relative humidity.
SWAT

Sub-model

Hydrological sub-model
- Water balance
- Water movement

Soil erosion sub-model
- Musle model

Pollution load Sub-model
- Transportation and fate of N, P
Water balance

\[ SW_t = SW_0 + \sum_{i=1}^{t} (R_{\text{day}} - Q_{\text{surf}} - E_a - W_{\text{seep}} - Q_{\text{gw}}) \]

- \( SW_t \): the final water content (mm)
- \( SW_0 \): the initial soil water content on day \( i \) (mm)
- \( t \): the time (days)
- \( R_{\text{day}} \): the amount of precipitation on day \( i \) (mm)
- \( Q_{\text{surf}} \): the surface runoff on day \( i \) (mm)
- \( E_a \): the amount of evapotranspiration on day \( i \) (mm)
- \( W_{\text{seep}} \): the amount of water entering the vadose zone from the soil profile on day \( i \) (mm)
- \( Q_{\text{gw}} \): the amount of return flow on day \( i \) (mm)
COMPONENTS OF SWAT

Major components can be grouped into two categories

(i) Land phase of the hydrologic cycle

- controls the amount of water, sediment, nutrient and pesticide loadings to the main channel in each sub-basin, and,

(ii) Routing phase of the hydrologic cycle

- defines the movement of water, sediments, nutrients etc. through the channel network of the watershed to the outlet.
Spatial data base was prepared in raster (grid) format

DEM which is one of the main inputs of SWAT Model was taken from ASTER DEM

Drainage map was extracted from DEM using channel threshold area of 45 sq km

Land use/land cover map was prepared using remote sensing data of Landsat ETM+

Soil map of the study area was digitized from soil map of NBSS &LUP at a scale of 1:50,000
DEM AND SUB BASINS OF BEAS BASIN (THALOUT)
DEM AND SUB BASINS OF BEAS BASIN (BHUNTER)
LAND USE AND SOIL MAPS OF BEAS BASIN (BHUNTER)
Comparison of a) daily observed and simulated stream flow hydrograph of Beas basin up to Bhunter during calibration period (1992-2000)
Comparison of a) daily observed and simulated stream flow hydrograph of Beas basin up to Bhunter during validation period (2001-2005)
Comparison of a) daily observed and simulated stream flow hydrograph of Beas basin up to Thalout during calibration period (1992-2000),
Comparison of a) daily observed and simulated stream flow hydrograph of Beas basin up to Thalout during validation period (2001-2005),
Daily calibration goodness of fit statistics for Beas river catchment

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Beas basin up to Bhunter</td>
<td>Beas basin up to Thalout</td>
</tr>
<tr>
<td>$R^2$</td>
<td>0.72</td>
<td>0.75</td>
</tr>
<tr>
<td>NSE</td>
<td>0.71</td>
<td>0.75</td>
</tr>
<tr>
<td>PBIAS</td>
<td>5.3 %</td>
<td>3.0 %</td>
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### WATER BALANCE (mm)

<table>
<thead>
<tr>
<th></th>
<th>P</th>
<th>ET</th>
<th>Sur_Q</th>
<th>LAT_Q</th>
<th>GW_Q</th>
<th>WYLD</th>
<th>Snowfall</th>
<th>Snowmelt</th>
</tr>
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<tbody>
<tr>
<td><strong>Beas basin up to Bhunter</strong></td>
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</table>
Spatial data base was prepared in raster format.

DEM which is one of the main inputs of SWAT Model was taken from ASTER DEM.

Drainage map was extracted from DEM.

Land use/land cover map was prepared using remote sensing data of Landsat ETM+.

Soil map of the study area was digitized from soil map of NBSS &LUP at a scale of 1:50,000.
DEM AND SUB BASINS OF GANGA BASIN (DEVPRAYAG)
LANDUSE AND SOIL MAP OF GANGA BASIN (DEVPRAYAG)
Comparison of a) scaled daily observed and simulated stream flow hydrograph of Ganga basin up to Devprayag during calibration period (1992-2000)
Comparison of: a) scaled daily observed and simulated stream flow hydrograph of Ganga basin up to Devprayag during validation period (2001-2005),
Mountain river hydrology is critical for downstream drinking water, agricultural irrigation, power generation, and flood management. Simulation and forecast of snowmelt runoff has become a real necessity in Himalayan region.

The increasing availability of remote sensing data facilitates the successful application of the model in the snow-dominated mountainous basins, where measured hydro-meteorological data are limited and/or not available at all.

Due to global climate change and global warming, snowmelt runoff research is considered more essential than ever before to predicting water resources availability, programing water usage and management.

More research should be encouraged on the feasibility of modeling snowmelt runoff in data-sparse mountainous watersheds by utilizing snow and glacier cover remote sensing data, GIS tools, field measurements, and innovative ways of model parameterization.