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Understanding future changes in snow and glacier melt runoff due to global warming in Wangar Gad basin, India

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Himalayas has one of the largest concentrations of glaciers and permanent snow fields. These are sensitive to climate change. Snow and glacier runoffs are important sources of water for the Himalayan rivers. Due to steep slopes, all these streams are potential sites for hydropower generation. To understand the power potential of small sub-basins, a snowmelt run-off model has been developed for Malana nala located in the Parbati river basin near Kullu in Himachal Pradesh and validated at the adjacent Tosh nala in the same basin. In the model, information generated through remote sensing techniques were used in conjunction with the daily maximum and minimum temperatures, rainfall and snow fall. This model is now extended to understand the effect of global warming in stream runoff and power generation.

To understand changes in runoff and power potential, possible changes in the input parameters were estimated by considering 1°C rise in temperature from 2004 to 2040. Snow line is calculated for 2040 using present altitude and lapse rate. Future change in areal extent of glacier and permanent snow were estimated using mass balance, response time and rate of melting at terminus for all glaciers in the basin. The model was validated for all seasons in 2004 and for selected seasons from 1997 to 2002. The error in runoff estimate was observed between 2 and 5%, except for the summer of 2002. The model suggests overall reduction in stream runoff by 8–28%, depending on the season.

OVER the past millions of years, the earth's surface has experienced repeated large periods of glaciations separated by short warm interglacial periods. During the peak of glaciations, an approximately 47 million sq. km area was covered by glaciers, three times more than the present ice cover of the earth[1]. Natural variations in the earth's orbit are well synchronized with atmospheric variations in methane and carbon dioxide, leading to repeated cycles of glaciations. However, this natural cycle might have altered due to the greenhouse effect, caused by man-made changes in the earth's environment. Some of the hypotheses suggest that this alteration might have started long before the beginning of the industrial revolution[2]. This has led to an increase in the global average temperature by 0.6 ± 0.2°C from 1900 (ref. 3). In addition, recent developments in climate modelling suggest that existing greenhouse gases and aerosols in the atmosphere have led to the absorption of 0.85 ± 0.15 W/m^2 more energy by the earth than emitted into space. This means additional global warming of about 0.6°C without further change in atmospheric composition[4]. This observation was further supported by the Fourth Assessment Report published by Intergovernmental Panel on Climate Change in 2007, where warming of 0.2°C per decade is projected for the next two decades, even if the concentration of all greenhouse gases and aerosols remain constant at the year 2000 level. In addition, best estimates of globally average surface air warming for different warming scenarios vary between 1.8°C and 4.0°C (ref. 5). This will have a profound effect on the Himalayan cryosphere.

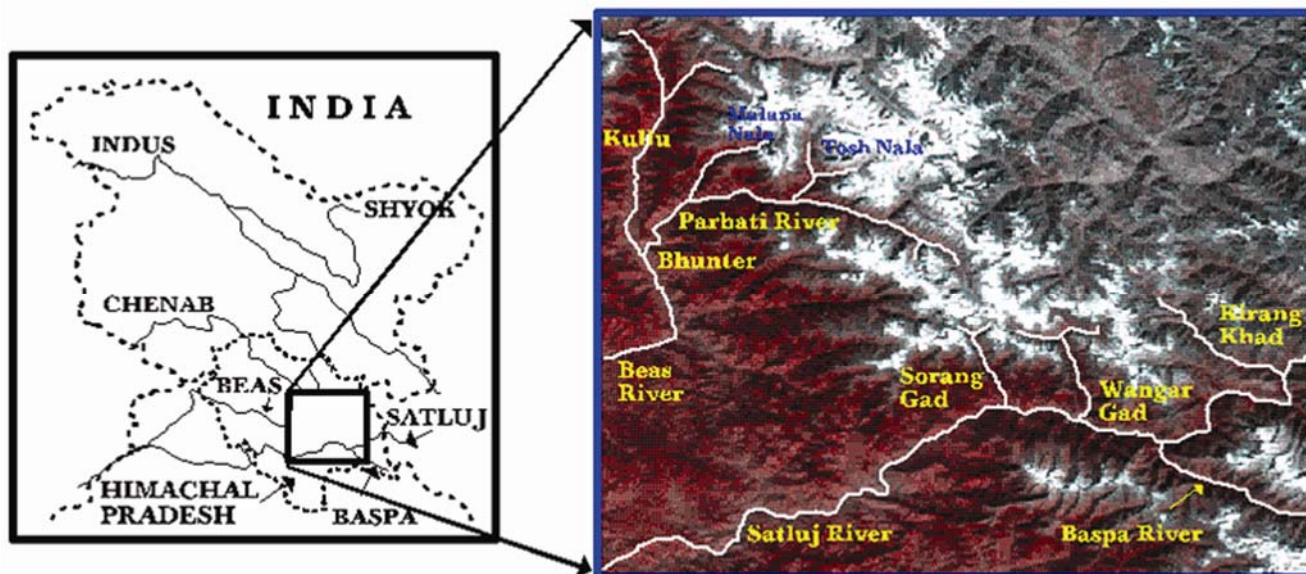*For correspondence. (e-mail: anil_vishnu@yahoo.com)

Figure 1. Location map of Wangar Gad.

In this communication, changes in runoff and power generation in Wangar Gad, a tributary of the Satluj river in Himachal Pradesh (Figure 1) due to rise in temperature by 1°C is discussed.

The snow and glacier melt run-off model was originally developed to estimate hydropower potential of snow and glaciated stream for winter, summer, monsoon and autumn seasons[6–8]. Information generated through remote sensing technique such as the areal extent of glaciers, permanent snow cover, seasonal snow cover, accumulation and ablation areas, altitude of snowline and glaciers were used in conjunction with the daily maximum and minimum temperatures, rainfall and discharge. Initially, the model was developed at Malana nala and then validated at Tosh nala in Himachal Pradesh. This model is now further modified to assess long-term changes in stream runoff due to changes in snow and glacial extent.

Average areal extent of snow for each month was estimated, using multi-date satellite data of WiFS and Advance Wide Field Sensor (AWiFS) of Indian Remote Sensing Satellite (IRS). A total of 66 scenes were analysed to estimate mean monthly and then weighted seasonal snow cover. Figure 2 shows AWiFS images of IRS P6 during autumn 2004. To estimate seasonal snow cover, supervised classification for WiFS and NDSI method for AWiFS was used[9,10]. A sample of AWiFS and NDSI imagery is given in Figures 2 and 3 respectively. To estimate snowline for 2040, a lapse rate of 140 m was added into the present snowline altitude. The lapse rate was estimated using field temperature data at the Chhota Shigri glacier[11]. Areal extent of permanent snow and glacier was estimated using IRS 1D LISS III image and distribution of glaciers is shown in Figure 4. To estimate areal extent of glaciers and permanent snow field in 2040,

information about mass balance, glacier thickness and rate of melting at the snout were used[12].

Mass balance was estimated using accumulation area ratio (AAR)[13]. AAR was estimated by analysing AWiFS images from June to September 2004. The glacial thickness was estimated using the empirical relationship between the glacier depth and area[14]. The change in glacial length was calculated using the specific mass balance and ablation rate at the terminus[15]. This relation was developed for the Himalayan region, where depth was estimated using geophysical technique in Nepal and China. The response time was estimated using glacial thickness and ablation rate at the terminus[16]. Daily maximum–minimum temperature and rainfall data of there years from 2001 to 2004 were used. This data for individual days were corrected for appropriate altitude using lapse rates[11]. The changes in glacial length were estimated using the following relationship[15].

$$L_1 = L_0 * (b/A_0),$$

where L_1 is the change in terminus length (m), L_0 the datum length or length of the glacier (m), b the decrease or increase in specific mass balance (m) and A_0 the ablation rate at the terminus (m/year).

Melt factor was estimated using empirical relationship with snow density[17]. General trend in snow cover density is taken from Bilello[18]. To estimate stream runoff, methodology given in the flow chart is adopted[8] and using the available head (H) in metres, hydropower is estimated[6].

In the Wangar Gad basin, 65 glaciers and permanent snowfields were mapped. Major glacier bodies with prominent snout points were demarcated. The model parameters for 2004 and 2040 are given in Table 1. Initially
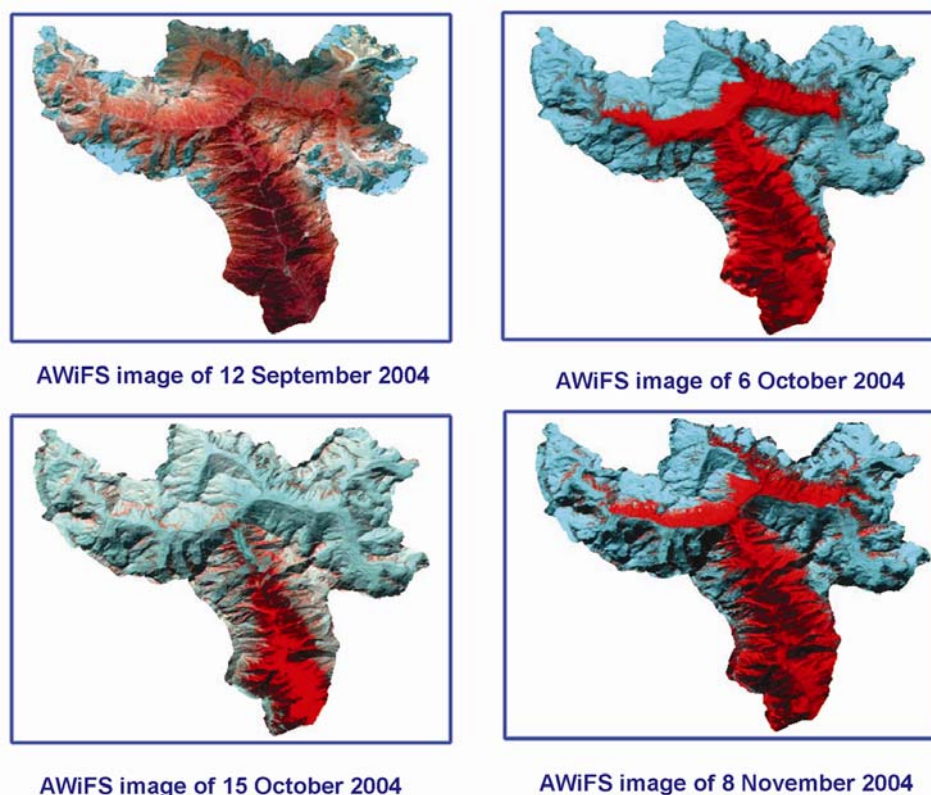
Figure 2. AWiFS images of IRS P6 showing snow cover during autumn 2004.

Table 1. Model parameters for the years 2004 and 2040

	Winter		Summer		Autumn		Monsoon	
	2004	2040	2004	2040	2004	2040	2004	2040
Snow extent (sq. km)	234	209	117	111	147	128	26	21
Glacier extent (sq. km)	40	16.4	40	16.4	40	16.4	40	16.4
Avg. snow line altitude (m)	3979	4140	4419	4588	4320	4488	4610	4778
Temp. index	0.0026	0.0023	0.016	0.016	0.0094	0.0088	0.028	0.027
Runoff (cumec)	4.10	3.33	15.97	14.62	9.65	7.67	22.45	16.14
Unrestricted hydropower (Mw)	27.55	22.39	107.11	98.07	61.36	51.45	150.58	108.31

Table 2. Validation of run-off model

Run-off	Observed runoff (cumec)	Model runoff (cumec)	% error
Autumn 2004	9.43	9.65	2.3
Winter 2004–05	4.26	4.10	3.5
Summer 2004	15.60	15.97	2.3
Monsoon 2004	21.56	22.45	4.1
Winter 1997–98	4.06	4.25	4.6
Winter 1998–99	4.68	4.43	5.2
Winter 1999–2000	3.07	2.90	5.7
Winter 2000–2001	3.52	3.69	4.7
Winter 2001–2002	4.03	4.2	4.9
Autumn 2000	7.72	7.45	3.4
Autumn 2001	8.11	7.73	4.7
Summer 2002	35.2	32.6	7.4

the snow and glacier melt run-off model was validated using stream runoff data of 2004 (Table 2). The estimates of stream runoff vary from 21.5 to 4.2 cumec in monsoon and winter respectively. The runoff estimates were also made for summer and autumn as 15.6 and 9.4 cumec respectively. The model estimates were compared with field observations and maximum error was observed for monsoon as 4.1%. The errors for other season were lower than monsoon (Table 2). The model was further validated using winter data from 1997–98 to 2001–02, autumn data of 2000 and 2001 and summer data of 2002. These seasons were selected depending upon systematic availability of historical satellite data. The error in runoff estimate was less than 7.5% and in a range of 4–5% (Table 2).
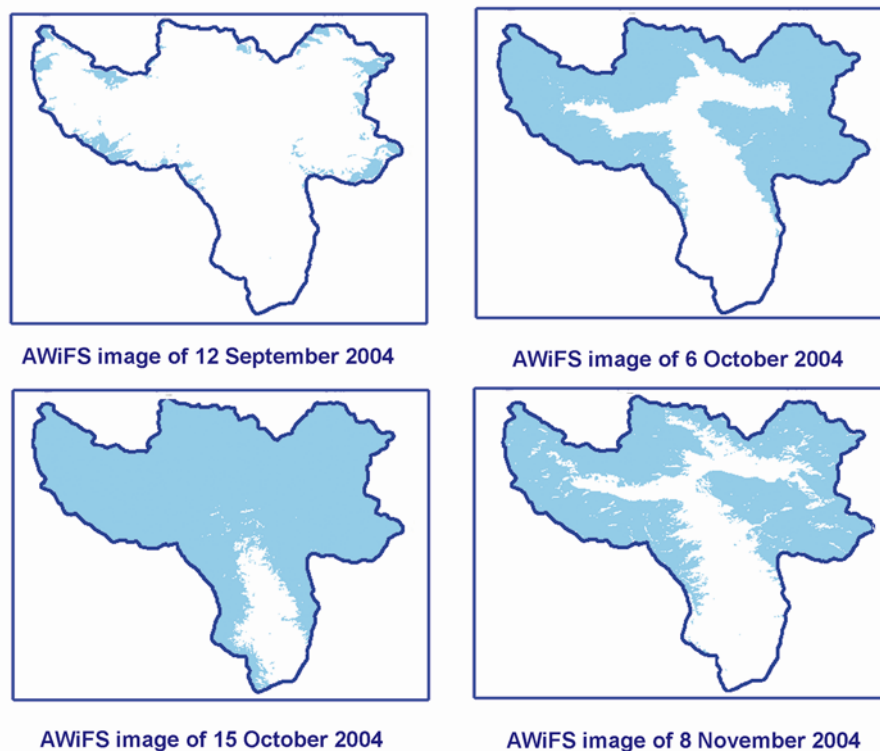
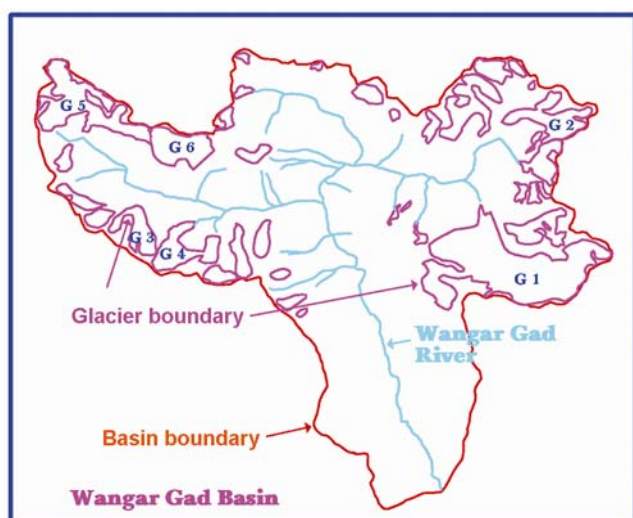**Figure 3.** NDSI images showing snow cover during autumn 2004.

Figure 4. Glacier, permanent snow, stream and basin boundary of 1962 from SOI map.

This suggests stability of model to estimate seasonal runoff.

In order to estimate stream runoff of 2040, possible changes in model parameters were estimated using methodology given in the earlier sections. Table 1 shows changes in input parameters, if atmospheric temperature rises by 1°C by 2040. Rise in temperature will influence snowline altitude, areal extent of seasonal snow and gla-

ciers. However, no major change in temperature index was observed, as it was estimated at mid-altitude. Mid-altitude is a mean of maximum and snowline altitude. This study suggests that stream runoff between 2004 and 2040 will reduce for Wangar Gad, a small tributary of Satluj river. However, change in runoff will vary from season to season. Maximum drop in runoff was estimated in monsoon season. In the model, amount of monsoon rainfall for 2004 and 2040 was the same. The model suggests that in 2004, glacier melt due to rain on glacier ice is an important source of stream runoff. During the same period, areal extent of seasonal snow is small and contribution of seasonal snow-melt on stream runoff is less. Therefore, by 2040, areal extent of glaciers will reduce by 59%, affecting stream runoff. On the other hand, less loss in stream runoff was estimated in summer (Table 1). In summer, i.e. between April and June, contribution of glacier melt into runoff is not high and most of the runoff is generated from seasonal snow melt. Due to area altitude distribution of Wanger Gad, no major change in seasonal snow extent is expected between 2004 and 2040. Autumn shows 20% loss in stream runoff due to change in glacial extent.

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A high-Si, high-Ca spinel-like phase from mantle peridotite: a report from Cretaceous ophiolite of Rutland Island, Andaman–Java subduction complex

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We report here exsolved phase with unusual composition (SiO_2: 14–22 wt%, CaO: 4–10 wt% and Cr_2O_3: 17–21 wt%) from mantle peridotite of the Cretaceous ophiolite of Rutland Island in the Andamans. This high-Si, high-Ca bearing spinel-like phase occurs in two modes as fine blebs ($<$1–3 μ) within exsolved blebs of diopside and fine lamellae ($<$1–7 μ) within the orthopyroxene host along with lamellae of diopside and Cr-spinel. The BSE image exhibiting a tonal character as well as the chemistry intermediate of Cr-spinel and diopside suggests that this phase exsolved from pigeonite at an intermediate stage before the exsolution of fine lamellae of Cr-spinel and diopside in the orthopyroxene host.

Keywords: Andaman, Mantle peridotite, Rutland Island, spinel-like phase.

SiO_2 can enter spinel structure by replacing Al_2O_3. Experiments demonstrate that a maximum of 28 wt% SiO_2 could be present as solid solution in Al–Si spinel structure[1]. SiO_2 solubility in spinel of lherzolite to harzburgite composition with olivine–orthopyroxene–spinel-clinopyroxene assemblage can increase in certain physico-chemical conditions. We report here a high-Si, high-Ca spinel-like new phase (*n*-spinel) from mantle peridotites represented by lherzolite to diopsidic harzburgite of the supra subduction zone ophiolite sequence of Rutland Island in the Andamans. An assemblage of exsolved grains of clinopyroxene–Cr-spinel–*n*-spinel occurs within large orthopyroxene porphyroclast of the mantle peridotites. The *n*-spinel also occurs within thick blebs of exsolved clinopyroxene. Apart from those exsolved phases, symplectites of pyroxene and spinel are also present in the mantle peridotites. The exsolved grains are formed during cooling process but symplectites of pyroxene and spinel are usually explained as the product of garnet breakdown due to decompression during the uprise of mantle[2–4]. The present observation of an intermediate phase in pyroxene–spinel stability field could address many problems related to the stability of spinel and Ca–Si solubility in spinel structure. This study has a signifi-

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