Damming rivers in the tectonically resurgent Uttarakhand Himalaya

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In the fault-ridden, seismically and tectonically active belts recurrently ravaged by excessive rains and resultant landslides in Uttarakhand, a very large number of big and small dams are being constructed and planned. Quite many of these projects suffered crippling damages during the 2013 disaster as mountain slopes slid down and floodwater severely eroded stream banks and dumped huge volumes of sediments on critical facilities. If the idea is to have environment-friendly power projects, then the planners and dam builders must not ignore the geological reality of the geodynamically sensitive region. Better sites for dams can be explored far upstream of the Main Central Thrust Zone.

Keywords: Hydroelectric projects, dams, landslides, seismicity.

Ambitious plan

THE vision of making Uttarakhand an *Urja Pradesh* (energy state) has inspired the state of Uttarakhand to embark upon an ambitious plan of having more than 180 big and small hydroelectric projects that are expected to generate more than 21,200 MW electricity (12,235 MW from just 95 projects in the Alaknanda and Bhagirathi valleys; *The Pioneer*, 4 July 2013). Most of these projects are located in the upper and middle reaches of 11 rivers (Figure 1) (Patni, B. D., pers. commun., 2013)[1,2].

From the structural map of Uttarakhand showing the locations of dams and the terrane-defining thrusts and faults, it becomes obvious that presumably three factors weighed heavily in the siting of these dams – (i) narrowness of the valleys, (ii) adequate water discharge in rivers, and (iii) head of water requisite for turning turbines of generators. It is also quite apparent that the structural layout (particularly related to faults and thrusts in the areas chosen) and the seismicity of the region were not taken into consideration. No thought was given to the need for preserving the environmental integrity and to the socio-economic problems the affected people will face or are facing.

Undeniably, the whole purpose of erecting dams is to generate electricity. Storage of water for irrigation and control of floods were secondary, if at all. None of the planned dams in Uttarakhand can therefore be described as multi-purpose projects (Tables 1 and 2). Most of the existing projects with installed capacity of nearly 20,000 MW are not able to generate more than half their generating capacity (Patni, B. D., pers. commun., 2013). Several dams and tunnels under construction are facing serious problems, such as washing away of barrages and coffer dams, onrush of water and finer sediments, blowouts and roof-collapse in tunnels associated with the projects, accumulation of sediments in reservoirs behind dams, malfunctioning or even stoppage of generator turbines due to excessive discharge of sediments, etc. during high floods and resultant loss of their economically useful life. The spectacle of devastation of a number of projects under construction was witnessed with stunning impact in mid-June 2013. This was to be anticipated, for the projects are sited in the structurally disturbed and tectonically over-stressed belt of seismicity, relentlessly battered by excessive rainfalls and cloudbursts (Figure 2).

Belt of the Main Central Thrust

The ever-snowy mountain ranges rising to heights of 5,000–8,000 m are known as the Great Himalaya or Himadri. It is made up of high-grade metamorphic rocks intimately associated with mylonitized (≡ milled and recrystallized) porphyritic granites and augen gneisses. A huge part of these rocks rides over the sedimentary and low-grade metamorphic rock assemblages of the Lesser Himalaya – the populated terrane of Uttarakhand. The southward thrusting of rock masses has taken place along a multiplicity of thrusts comprising the Main Central Thrust (MCT) zone (Figures 2 and 3). The three important thrusts of the MCT zone are the Munsiari Thrust at the bottom, the Vaikrita Thrust in the middle and the Pindari Thrust at the top[1,3–6]. A thrust never occurs alone; it is always associated with parallel, sub-parallel thrusts branching off from the main thrust. The result is the formation of imbricate piles of sheets and slabs of deformed and sheared rocks (Figures 3 and 4). It may be emphasized that the Himalayan province is not only dissected by ENE–WSW trending rather northward gently dipping

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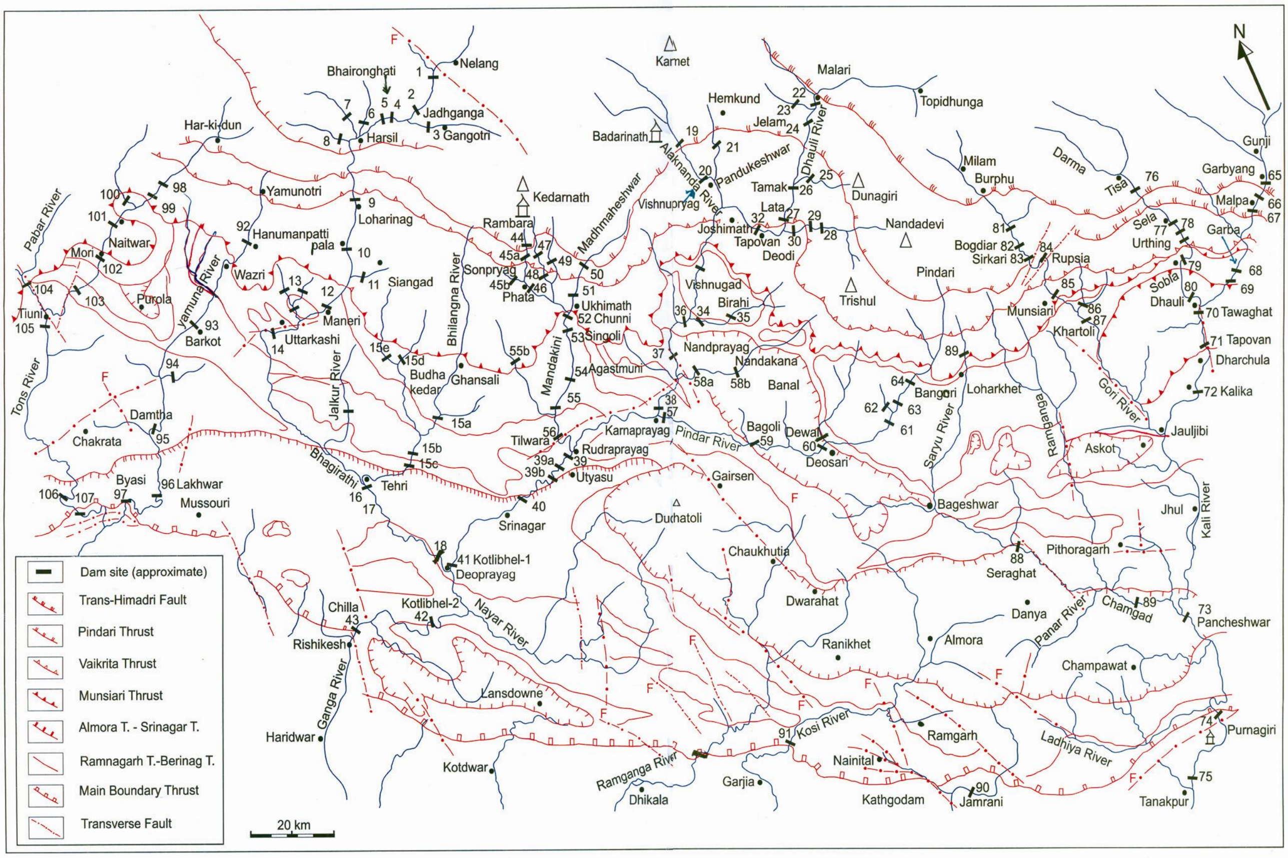

Figure 1. Structural map of Uttarakhand showing locations of big dams (height >25 m) in existence, under construction and those planned. The positions of dams are approximate. The structural elements comprise major thrusts and transverse (tear) fault dissecting the land. (Map after Valdiya[1] and location of dams after Thakkar[2] and Patni (pers. commun., 2013)).

Table 1. Existing, under construction and proposed hydroelectric projects in Uttarakhand (after Thakkar[2])

River	Existing	Under constriction	Proposed	Total
Bhagirathi	13	13	22	48
Alaknanda	32	16	74	122
Mandakini and Pindar	4	2		6
Ramganga	12		20	32
Kali (including Gori and Darma)	28	8	48	84
Yamuna	9	2	33	44

Table 2. Number of hydroelectric projects in Uttarakhand (after Thakkar[2])

River	Big (>25 MW)	Small (1–25 MW)	Total
Bhagirathi, Bhilangana	5	13	18
Alaknanda, W. Dhauli, Birahi, Pindar	29	43	72
Ramganga	6	12	18
Kali, Darma, Gori	26	16	42
Yamuna	17	13	30

thrusts, but is also torn by NW–SE, NNW–SSE, N–S and NNE–SSW trending nearly vertical dip–slip, net slip and strike–slip faults, which have pronouncedly wrenched the rock piles (Figure 1).

As the northward-moving Peninsular India presses on, the Lesser Himalaya rock assemblages are compressed, and are pushed under the huge pile of the Great Himalayan rocks, the latter riding southwards onto and over the Lesser Himalaya.

The movement has been going on since the MCT was formed 20–22 million years ago. This movement is not continual but intermittent, rather episodic.

As a consequence of episodic movements on active thrusts, there is compression and squeezing of the Lesser Himalayan rock assemblages, their bending and sliding along inter-formational thrust planes of the MCT zone. This has resulted in a number of thrust planes coming in closer proximity just south of the southern slopes of the Great Himalaya (Figures 1, 2 and 3). Another consequence of the repeated movement is shearing, shattering

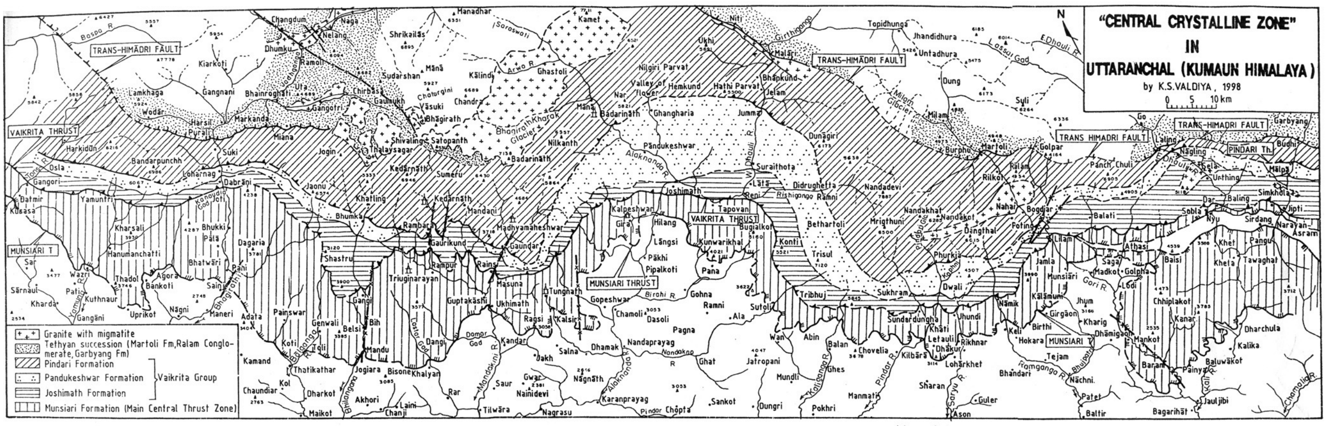

Figure 2. The Main Central Thrust (MCT) zone in Uttarakhand comprising long, deep thrust planes, including the Munsiari Thrust, the Vaikrita Thrust, and the Pindari Thrust. Besides these three principal thrust planes, there are a large number of thrusts and faults sub-parallel to or branching from them; quite a few of them are active (after Valdiya *et al.*[3]).

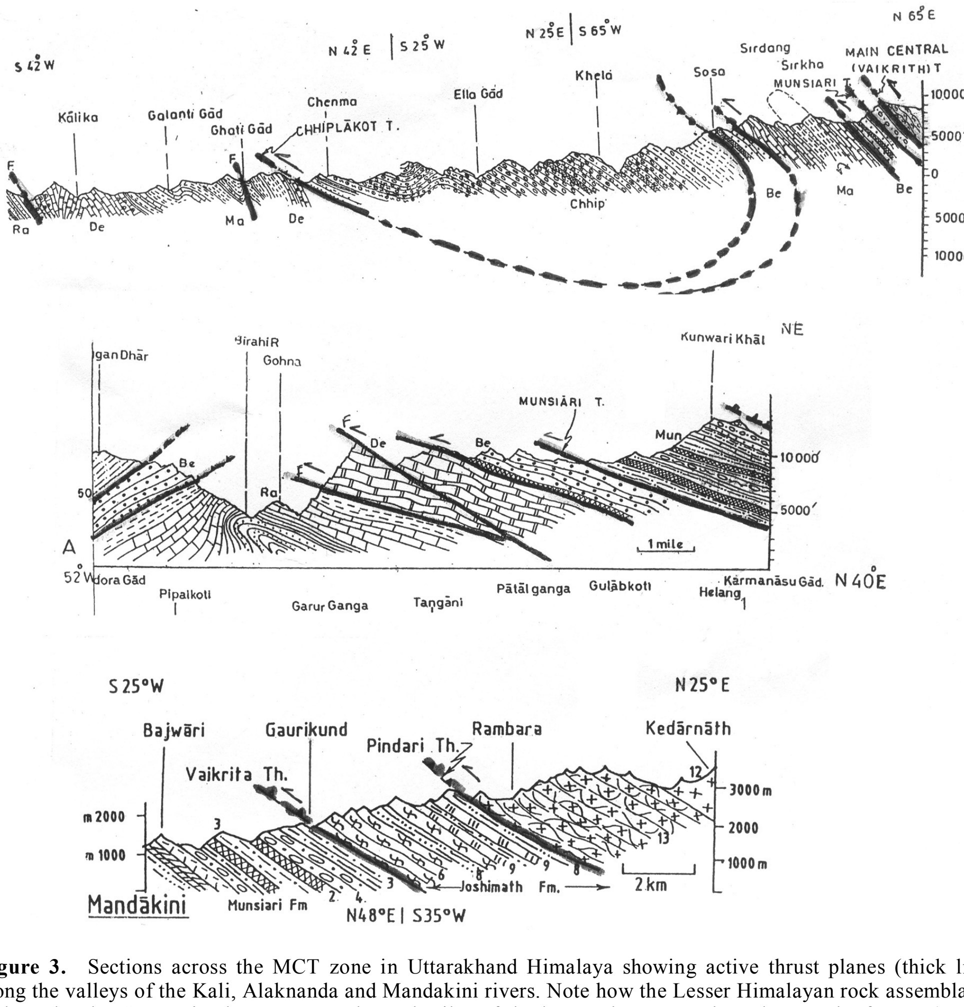

Figure 3. Sections across the MCT zone in Uttarakhand Himalaya showing active thrust planes (thick line) along the valleys of the Kali, Alaknanda and Mandakini rivers. Note how the Lesser Himalayan rock assemblages slide under the Great Himalaya, even as the rock piles of the latter advance southwards over the former (Lesser Himalayan assemblages) (after Valdiya[1,5]).

and even pulverization of rocks, resulting in considerable weakening of rocks. The weakened rocks are easily vulnerable to seismic shocks, rains, frost action and to the imprudent activities of humans.

Neotectonic activities

Investigations carried out along the rivers Kali, Darma (Eastern Dhauli), Gori, Western Dhauli, Alaknanda, Mandakini and Bhagirathi demonstrate that practically all thrusts of the MCT zone, and quite many of the Lesser Himalayan terrane are neotectonically active. These have been active in the Late Quaternary times, including the Holocene. In other words, there were backward–forward, sideways and up-and-down movements on them, particularly since about 60,000 years[4,6–13].

The Joshimath area (Figure 2) has been intermittently sinking over a long belt for quite many decades owing to the activeness of the Vaikrita Thrust that passes by.

The incidence of prolonged rock falls and slumping of rock-masses even during dry seasons witnessed in the Kali and Gori valleys in the east, imply continuing movement at present on some of the faults of the MCT zone. This is further borne out by occurrence of earthquakes all along the belt, just south of the Great Himalayan axis (Figure 5). Needless to state that earthquakes result from movements on planes of rupture which may or may not reach the surface.

The metamorphic and granitic rocks of the Chhiplakot massif in eastern Kumaun have been rising up. The rock assemblages above the Vaikrita and Munsiari thrusts of the MCT zone are exhumed or pushed up at the rate of 1.2–3 mm/yr (ref. 14). Geodetic levelling and GPS investigations demonstrate that the whole of the Lesser Himalaya in Nepal is rising at the rate of ≤ 3 mm/yr, while the Great Himalaya is gaining height at the rate more than 5 mm/yr (ref. 15). The rise of mountains is attributed to movements on active faults. Faster uplift together with environmental degradation has accelerated the rate of denudation – it is more than 6 mm/yr in a part of central Nepal[16], and could be no less in the tectonically ravaged terrains of Uttarakhand. The inevitable consequence of voluminous accumulation of erosion-generated sediments is the progressive shallowing of channels, and frequent and more destructive floods. It happened this time around because enormous volume of debris had been dumped in the river valleys by the builders of roads and dams. In a number of reaches of rivers, the river beds rose by 10–20 m!

The geomorphic peculiarity of the Himalaya bears eloquent testimony to the continuing uplift of the land. In the Great Himalayan domain, river valleys are characterized by gorges with nearly vertical to convex walls and slit canyons in the proximity of active faults marked by pronounced knick points on river beds.

In the Lesser Himalayan terrain, the commonly wider valleys with gentle valley slopes abruptly narrow down to canyons and gorges close to the active terrane-defining thrusts (Figure 6). These features imply faster uplift of

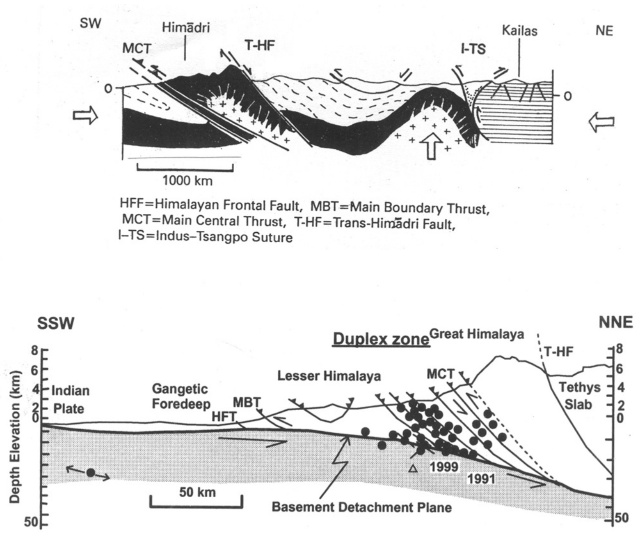

Figure 4. The zone of imbricating pack of thrust sheets and slabs, resulting from repeated and strong movements along the thrust planes of the MCT. The hypocentres of the aftershocks of 1991 and 1999 earthquakes in Garhwal are related to the imbricate zone (after Kayal[17]).

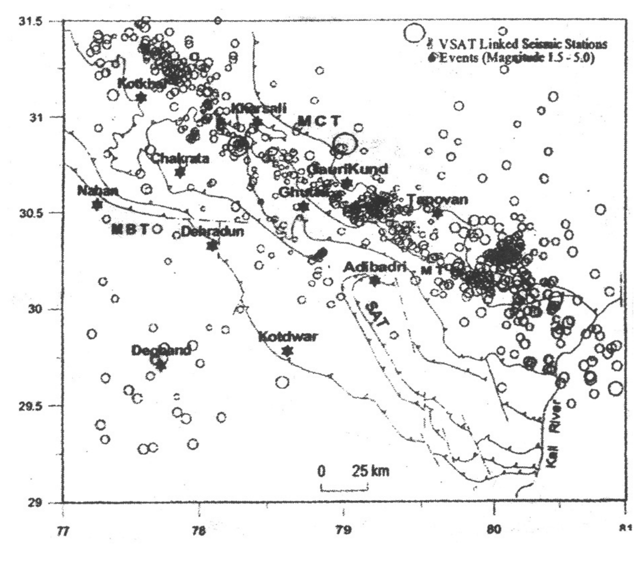

Figure 5. Distribution of epicentres is concentrated in the nearly 50 km wide belt of the MCT zone. Note, some areas register more frequent earthquakes (after Paul *et al.*[22]).

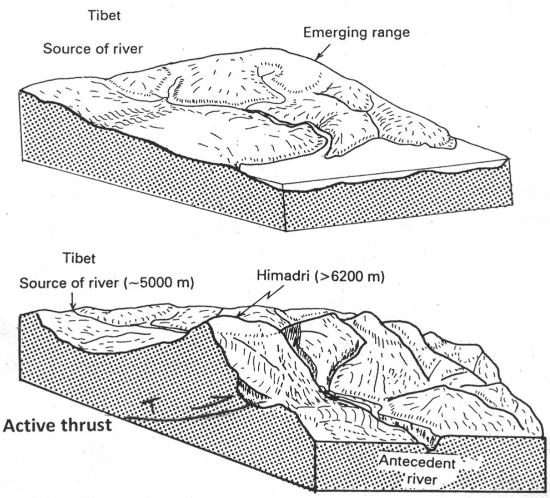

Figure 6. Evolution of a gorge as the hill gradually rose due to movement on an active thrust plane.

rock masses on the planes of discontinuity (fault or thrust). Moreover, terraces lining these valleys represent sediments deposited by rivers as their bed gradient lessened due to uplift and/or resultant blockage (Figure 7). Thus, the narrow gorges and riverine terraces upstream of these gorges testify to the fact that there were upward movements on the active thrusts and faults in the not-too-distant geological past. Stepped terraces indicate more than one spurt of uplift. Commonly there are three levels of terraces, implying as many episodes of upward movements on active faults and thrusts. In quite many areas there are more than three levels of terraces, indicating repeated movements on thrusts.

Seismicity condition

The MCT zone is seismically the most active belt of Uttarakhand, where maximum strain build-up is taking place. Most of the epicentres of moderate earthquakes ($M \geq 5$) are concentrated in a narrow (50 km) zone (Figure 5). Focal mechanisms demonstrate that most of the events are related to shallow (≤ 30 km) thrusting. The October 1991 Uttarkashi earthquake (M_b 6.6) and the March 1999 Chamoli earthquake (M_b 6.3) originated at a depth of 12–15 km, and their aftershocks[17] occurred all over the imbrication zone of thrust sheets (Figure 4).

The 1999 Chamoli earthquake is related, in my opinion[1,7], to the extremely active Nandprayag Fault. This fault (Figures 1 and 2) generated aftershocks by strike–slip mechanism[17]. Soft-sediment deformation features in the riverine sediments[18] corroborate the inference that this area is recurrently affected by tectonic movement. Likewise, deformation of soft fluvial sediments in Uttarkashi area cut by a N–S trending Henna fault indicates that this whole Chamoli–Uttarkashi belt has been experiencing unbearable tectonic stresses[19].

The Kapkot–Dharchula area and adjoining Darchula–Bajang area in NW Nepal are frequently rocked by earthquakes of M 5 to 6.5. From the quantitative seismicity map of the Himalaya[20], it is apparent that if one goes by

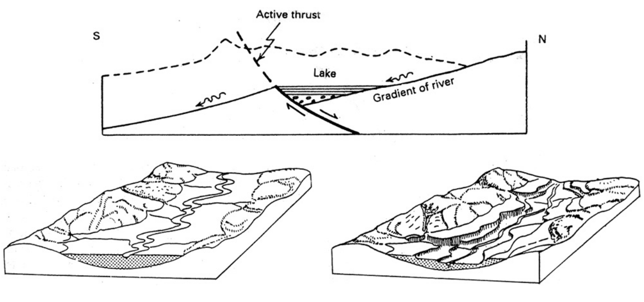

Figure 7. Due to uplift on a fault/thrust plane and heaving up of the ground, the gradient of the river bed decreases, causing deposition of its sedimentary load. Subsequent spurts of uplift are responsible for the formation of many levels of terraces – the evolution of stepped terraces. (Diagrammatic sketches after Valdiya[5].)

the number of earthquakes of $M \leq 5$, this part of the Himalaya (Kapkot–Dharchula–Bajang) shows highest seismicity anywhere in the Himalaya. Myriads of micro-earthquakes occur in this region[21].

Analysis of 312 out of 2000-odd events of $M \leq 4.5$ during the period 1999–2004 indicated that the strain accumulated in the stressed rock masses of Uttarakhand is released by the NNW–SSE and N–S trending faults[22], corroborating the inference of Valdiya[4,7].

Zones of endemic–recurrent landslides

It has been stated that repeated movements on the multiplicity of thrusts and faults have caused shearing, shattering and breaking of rocks, which were already mylonitized (milled and recrystallized) in the distant past. The rocks making the southern slope of the Great Himalaya and the adjoining mountain ranges of the Lesser Himalaya are thus in a very weakened state, and therefore extremely vulnerable to seismic shocks and battering of rains. Even small tampering with the precarious balance, such as digging for house-building and quarrying can have adverse effect on the slope stability. Excavations related to mining and road network have greatly destabilized the slopes, triggering unending rock falls, landslides and debris avalanches during heavy rains. Denuding the slopes of their protective forest cover has considerably aggravated the problem of hazard from mass-movements. Pointing to the fact that there are a number of active faults, there is a high seismicity, and the landslides are frequent and large in dimension in the narrow MCT belt (Figure 8), I had suggested complete banning of deforestation, mining and expansion of settlements, and minimum road-building activities in this extremely vulnerable belt[23].

Excessive rainfall and cloudbursts

To compound the tragedy resulting from frequent earthquakes and large-scale landslides, there has been excessive rainfall, quite often extremely heavy rainfall over limited geographic area at a time, for the last 7–8 years[24]. The mid-2013 calamity that befell Uttarakhand demonstrated the enormity of the hazard that stalks the land of the MCT zone.

Locations of hydroelectric projects

Realizing that there is no adequate arable land and industrial manufacturing base in the larger part of Uttarakhand, only the hydroelectric potential provides the means to finance economic growth and social development as seems to be happening in Bhutan. It is therefore necessary that the state harnesses its rivers for energy generation. However, the sites must be chosen carefully taking into

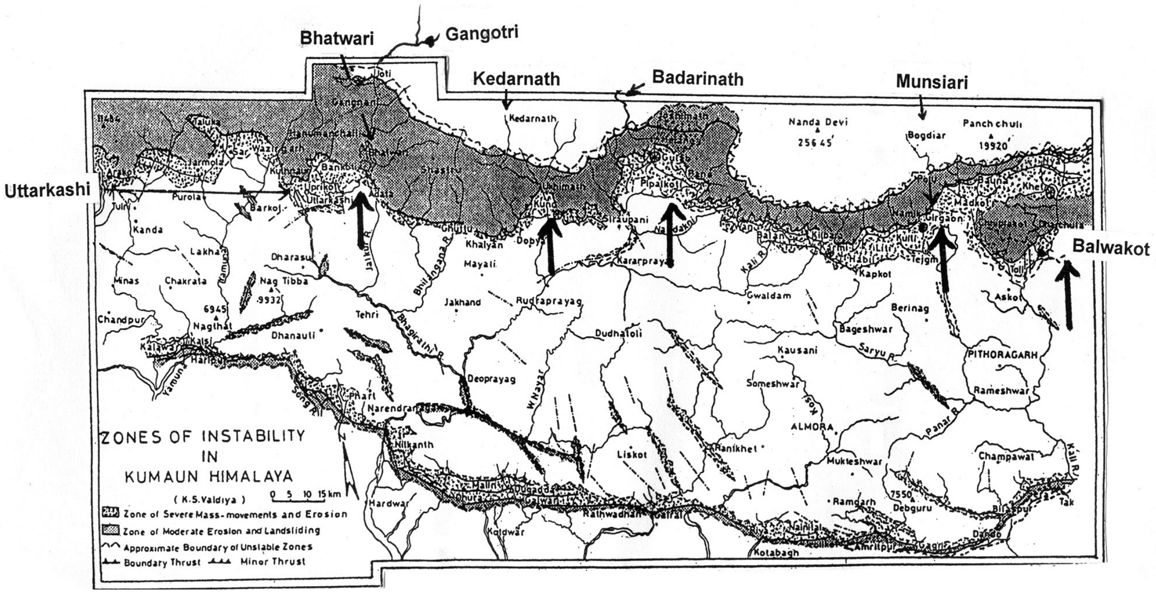

Figure 8. The MCT zone, characterized by active thrusts, endemic landslides and recurrent earthquakes, is a belt of unstable slopes vulnerable to seismic shocks, battering of rains and human activities (after Valdiya[23]).

consideration the geological and ecological factors, independent assessment of benefits to the local people and the country at large and control on the management of the projects.

It will be obvious from the distribution of dam locations (Figure 1; Tables 3–6) based on information culled from reports of Central Electricity Authority, Uttarakhand Hydroelectricity Nigam, Uttarakhand Renewable Energy Development Authority, etc. that the existing hydroelectric projects and those that are under construction or planned are sited close to the terrane-defining thrusts known to be active. The sites were chosen presumably in the narrowest stretches of the river valleys, little realizing that the otherwise wide valleys with gentle valley sides become narrow with steep to nearly vertical walls due to uplift of the ground and attendant accelerated riverbed erosion as explained earlier. The ground rises as a consequence of upward movement on active faults/thrusts (Figure 6). Moreover, the belts of active faults are made up of deformed rocks – many-times folded, sheared, shattered an even crushed rocks. These rocks understandably easily break-up, fall-off, creep and slide or slump down when excavated or shaken by earthquakes and explosions, and sink under loads. These incidences are bound to pose a threat to the various structures built in the project areas. The development of hydroelectric projects not only entails excavations for the head race dams and associated coffer dams, diversion tunnels, main tunnels for carrying water to turbines, and multitudes of adits, but also for the network of roads, for residential colonies for work force, and for power generators. Obviously, a dam site – no matter if it is just a small one – is excessively subject to tampering with the natural balance in a zone of very weakened rocks.

Reactivation of the active thrusts is bound to impact the stability of the engineering structures. One of the impacts could be the displacement or disruption of the structures due to sudden release of stress that the thrust movements entail. The effects on the tunnels associated with dams would be far more severe – there would be disruption or offsetting of tunnel, roof collapse, sudden onrush of interstitial groundwater with crushed material, and severe damage to tunnel lining. The very making of a tunnel is like opening an underground drainage and thus altering the groundwater regimes of the mountains, resulting in drastic lowering of groundwater table and attendant drying up of springs and dwindling of surface flow in streams.

Figure 1 is self-explanatory. Needless to state that a large number of existing and planned hydroelectric projects are bound to encounter serious problems, particularly if and when movements take place on the thrusts in the proximity of the project locations.

Seismicity factor

Movement on thrust planes and along faults triggers shaking of the ground, and unlocking on those on which movements have got struck due to unevenness of the planes would generate larger or great earthquakes. Unless the dams are designed to withstand peak ground acceleration of about 0.44 g (caused by earthquakes of $M \geq 7$), they may face the problem of disconnection with their abutments and sliding if they are erected on slippery rocks (such as schists), and of overtopping of dam due to waves generated in the impounded water of reservoirs behind dams, besides slope failures and attendant mass-movements.

Table 3. Hydroelectric projects in the Ganga Basin (after Thakkar[2])

River	Project (no. given in Figure 1)	Dam height (m)	Head race tunnel length (km)	Power generation (MW)	River	Project (no. given in Figure 1)	Dam height (m)	Head race tunnel length (km)	Power generation (MW)
Bhagirathi	Loharing–Pala*	15	13.8	600	Alaknanda	Alanknanda (Badarinath)	18	2.9	300
Bhagirathi	Pala–Maneri*	78	12.5	480	Alaknanda	Vishnuprayag (Lambagar)	14	12	400
Siyang	Siyangad*			11.5	Alaknanda	Bhyundar*			24
Siyang	Maneri-I[#]	39	8.6	90	Alaknanda	Vishnugad–Pipalkot	65	13.4	444
Siyang	Maneri–Bhali[#]		16	304	Alaknanda	Baula–Nandprayag			300
Siyang	Tehri-I[#]	260.5	3.2	1000	Alaknanda	Nandprayag–Langasu			100
Siyang	Koteshwar*	97.5		400	Alaknanda	Karnaprayag			160
Siyang	Kotlibhel-1A*	80.5	1.45	195	Alaknanda	Utyasu-I			70
Siyang	Kakoragad*			12.5	Alaknanda	Utyasu-II			205
Siyang	Jalandharigad*			24	Alaknanda	Utyasu-III			195
Siyang	Asiganga-I, II, III*			16.3	Alaknanda	Utyasu-IV			125
Siyang	Harsil[#]			2	Alaknanda	Utyasu-V			80
Siyang	Bhaironghati-I			380	Alaknanda	Shrinagar*	0.3		330
Siyang	Bhaironghati-II			65	Alaknanda	Kotlibhel-IB*	90		320
Siyang	Gangotri		5.2	24	Birahi	Gohna Tal		99	60
Jadhganga	Karmoli		8.6	140	Birahi	Birahi Ganga*			2.4
Jadhganga	Jadhganga		1.1	50	Birahi	Birahi-I[#]			7.2
Bhilangana	Bhilangana-I			22.5	Pindar	Buara			14
Bhilangana	Bhilangana-II			63	Pindar	Melkhet			15/56?
Bhilangana	Phalendra (Bhilangana-III)			24	Pindar	Dewal[#]			5
Bhilangana	Balganga-2			7	Pindar	Deosari			255/300?
Bhilangana	Kot Budhakedargad			6	Pindar	Mingalgom			114
Bhilangana	Jakhoti (Dharmganga)			12.5	Pindar	Bangari			44
Mandakini	Rambara		7	76	Pindar	Padli			27
Mandakini	Gaurikund			18.6	Pindar	Deoli*			13
Mandakini	Sonprayag			7	Pindar	Banal			10
Mandakini	Kaliganga-1*			4	Pindar	Bagoli			72
Mandakini	Kaliganga-2*			6	Western Dhauli	Malari–Jelam		4.5	55
Mandakini	Madniganga			10	Western Dhauli	Kosagad			24
Mandakini	Madhmaneshwar-I*		2.6	10	Western Dhauli	Jelam–Tamak		2.6	60
Mandakini	Madhmaheshwar-II		3	6	Western Dhauli	Dunagrigad			10
Mandakini	Phata–Byung*	26	9.4	76	Western Dhauli	Tamak–Lata		5.7	280
Mandakini	Chuni–Semi			24	Western Dhauli	Lata–Tapovan*	24.5	7.5	310
Mandakini	Singoli–Bhatwari*	12.5	12	99	Western Dhauli	Tapovan–Vishnugad*	22	12	520
Mandakini	Agastmuni			25	Western Dhauli	Rishiganga-II			35
Mandakini	Vijaynagar–Tilwara			40	Western Dhauli	Rishiganga-I			70
Mandakini	Tilwara–Rudrapryag			20	Western Dhauli	Deodi		4.5	60
Mandakini	Lastargad			6	Ganga	Kotlibhel-II*	82	3.1	530
Mandakini	Rampur–Tilwara			25	Ganga	Chilla[#]			144

[#]Existing; *Under construction.

Seismologists predict that this region is likely to be rocked by earthquakes much stronger than *M* 7 (ref. 25) it would be safer to design dams that can withstand peak ground acceleration as high as 1.0 g (ref. 25).

I wonder how many of the dams built, under construction and those planned have designs that can survive large earthquakes.

Loss of storage capacity of reservoirs

While the Lesser Himalayan terrane in Nepal is rising at the rate of >3 mm/yr, the Great Himalaya is gaining height at a much faster rate of > 5 mm/yr, as already stated[15]. Faster rate of erosion has triggered accelerated erosion in the resurgent Himalayan province. Implied is the fact of enormous volumes of eroded material finding their way into river valleys and in the natural and artificial lakes. Then there are voluminous masses of debris generated by myriads of landslides and rock falls. Understandably, the fine sediments and debris filling the reservoirs formed behind the dams are rapidly losing their water-holding or carrying capacity. In other words, the economically useful life of the reservoirs is diminishing rapidly. It is well known that on an all-India basis, the sediment infilling is taking place at the rate 1.5–3 times more than anticipated at the designing stage.

The mid-June 2013 calamity in Uttarakhand resulting from excessive rainfall, with cloudbursts in the Kedarnath

Table 4. Hydroelectric projects in the Kali Basin (after Thakkar[2])

River	Project (no. given in Figure 1)	Dam height (m)	Head race tunnel length (km)	Power generation (MW)
Kali	Garbyang			131
Kali	Budhi			192
Kali	Malpa			138
Kali	Garba–Tawaghat			610
Kali	Tawaghat–Tapovan			105
Kali	Tapovan–Kalika			160
Kali	Tapovan–Chunar			485
Kali	Kalika–Baluwakot			120
Kali	Kalika–Dantu			230
Kali	Pancheshwar	290		6000
Kali	Purnagiri			1000
Kali	Tanakpur			94.5
Darma (Eastern Dhauli)	Bokang–Baling			330
Darma (Eastern Dhauli)	Sela–Urthing			230
Darma (Eastern Dhauli)	Urthing–Subla			340
Darma (Eastern Dhauli)	Sobla–Jhimjhimgaon			145
Darma (Eastern Dhauli)	Dhauliganga (Khet)	56	5.4	280
Darma (Eastern Dhauli)	Chhungarchal		4.2	240
Gori	Mapang–Sirkari			340
Gori	Bogdiar–Sirkari			170
Gori	Sirkari–Rupsiabagar			210
Gori	Rupsiabagar–Khasiabagar			260
Gori	Goriganga–Munsiari			140
Gori	Madakinigad			13.5
Gori	Khartoli–Lumti Talla			55
Saryu	Loharkhet			5

Table 5. Hydroelectric projects in the Yamuna Basin (after Thakkar[2])

River	Project (no. given in Figure 1)	Dam height (m)	Head race tunnel length (km)	Power generation (MW)
Yamuna	Hanumanchatti–Synachatti			33
Yamuna	Barkol–Kuwa			42
Yamuna	Barnigad–Naingaon			30
Yamuna	Damtha–Naingaon			20
Yamuna	Lakhwar	204		300
Yamuna	Byasi	86	2.7	120
Tons	Sankri–Mori			78
Tons	Taluka–Sankri			140
Tons	Jakhol–Sankri			45
Tons	Naitwar–Mori			60
Tons	Mori–Hanol			63
Tons	Hanol–Tiuni			60
Tons	Arakot–Tiuni (Pabar R.)			81
Tons	Tiuni–Plasu			60
Tons	Chammi–Naingaon			540
Tons	Kishau			600
Tons	Chatra			300
Tons	Chibro			240
Tons	Khodri		5.6	120

and Munsiari–Dharchula regions, resultant landslides of unimaginable proportion and unprecedented floods in the Bhagirathi, Mandakini, Alaknanda, Pindari, Gori, Darma (Eastern Dhauli) and Kali rivers brought out the enormity of the problem of excessive generation of debris and its fallout in the reservoirs created – such as one behind the dam in the Eastern Dhauli between Tawaghat and Khet which lost nearly 80% capacity of holding water and the Vishnuprayag project in the Alaknanda where the debris caused crippling damage (Figure 9). It is obvious that the dams would not be able to serve their purpose of generating electricity if the landslides and mass-movements are not prevented from happening. In view of the builders of roads and dams cutting the unstable mountain slopes recklessly and relentlessly, the prevention of landslides is a tall order.

One example would suffice to illustrate the point. The 150-m high Kulekhani Dam, SW of Kathamandu in Nepal, is being filled with sediments by the river and its tributaries – all of them forming deltas at the points of streams meeting the reservoir. The deltas grew progressively downstream, eventually overwhelming the whole of the lake. The result was an alarming loss of water-holding capacity of the reservoir. The original storage capacity of 85.3 million m^3 in 1982 dwindled to 78.3 million m^3 by July 1993, the sediment having been eroded from the catchment at 31,700 $m^3/km^2/yr$ (ref. 26). A single rainstorm event deposited 4.8 million m^3 of sediment at the rate of 31,700 $m^3/km^2/yr$ (ref. 26). Now in the MCT zone such rainstorms have become more frequent and much widespread in the last 7–8 years. One can imagine what would happen to the reservoirs formed behind dams.

Table 6. Proposed hydroelectricity projects in the Saryu–Ramganga valleys (after Thakkar[2])

Project	District	Power generation (MW)
Khatri	Bageshwar	63
Luni	Bageshwar	54
Kuargad	Bageshwar	45
Khutani	Bageshwar	18
Saryu-I	Bageshwar	7.5
Saryu-II	Bageshwar	15
Saryu-III	Bageshwar	10
Balighat	Bageshwar	5.5
Baliar	Almora	88
Seraghat	Almora	10
Chamgad	Pithoragarh	?

Figure 9. Flood filled the Alaknanda channel behind the Vishnuprayag dam with debris, inflicting crippling below to the project (courtesy: B. D. Patni).

High dams north of MCT zone

North of the MCT zone, the wide swathe of high mountain domains offers much better and relatively safer sites for high dams. Not only the narrow gorges in the Great Himalayan and Tethys Himalayan domain provide ideal locations, but also there would be considerably less environmental, social and economic problems. Bereft as these domains are of forest cover, there are practically no human settlements and agricultural fields. Therefore, there will be no problems of deforestation and uprooting of the people. However, landslides, rock falls, and avalanches will be quite common, particularly in the belts cut by faults, such as the Trans-Himadri Detachment Fault[8].

It is not to be construed that the domain (upstream) north of the MCA zone is free from severe folding, faulting and thrusting. Indeed there are severe folds, faults and thrusts aplenty. Since the faults and thrusts of the MCT zone and of the Trans-Himadri Detachment Fault system together by themselves accommodate considerable amount of strain, there would be relatively lesser incidence of earthquakes and attendant slope failures in the terrane between these two fault systems.

In the Tethys domain the wind blows strongly after about 11 A.M. until sunset[24]. If the hydroelectric power projects can be tied up with multiple projects of harnessing wind energy, Uttarakhand would indeed become an *Urja Pradesh*.

Plea for smaller dams

I have been pleading for smaller dams with reservoir capacity of 50,000–1,00,000 m^3 and power generation potential of 5 MW (refs 24, 27–29). The smaller dams are to be located not only on rivers but also on the multitude of tributary rivulets with adequate water discharge.

China provides an inspiring example of tapping stream water in an environmentally sound and economically rewarding manner. As far back as 1985, China had built nearly 80,600 small hydro-power stations that produced an aggregate amount of 8000 MW electricity of the total 20,000 MW hydroelectricity generated. The basic design of small hydro-power projects incorporates storage, retention, diversion and interconnection of stream waters, and concurrently generating electricity while the lower reaches of rivulets serve as storage basins.

In what Zheng Naibo[30] described as Cascade Development Scheme, streams joining *small* rivers (or rivulets) are utilized to harness hydro-power and store water. In a chosen catchment, small dams not more than 10–30 m high are constructed across perennially flowing streams. Using stream drops, the dams create head-water reservoirs for increasing the firm capacity of downstream power-producing stations (Figure 10). Tunnels from these many reservoirs bring down gushing waters to a single

Table 7. Expenditure and benefits from major and minor irrigation projects (Planning Commission statistics; after Singh[31])

	Quality/expenditure (million rupees)		Cumulative potential (million hectares)	
	Major/medium	Minor	Major/medium	Minor
Pre-plan benefits	–	–	9.70	12.90
First plan	3,800	760	12.20	14.06
Second plan	3,800	1,420	14.30	14.79
Third plan	5,810	3,280	16.60	17.01
Annual plan 1966–1969	4,340	3,260	18.10	19.00
Fourth plan 1969–1974	12,370	5,130	20.70	23.50
Fifth plan 1974–1978,	24,420	6,310	24.82	27.30
1978–1979	9,770	2,370	25.86	28.60
Annual plan 1979–1980	10,790	2,600	26.60	30.00
Total	75,100	12,930	168.88	187.16

Table 8. Comparison of big dam with a series of smaller dams in a river in USA (after Odum[32])

	Mainstream reservoirs behind a big dam	Multiple-head water reservoirs behind smaller dams
Number of reservoirs	1	34
Drainage area (sq. miles)	195	190
Flood storage (acre-feet)	52,000	59,100
Surface water for recreation (acres)	1,950	2,100
Flood pool (acres)	3,650	5,100
Bottom inundated and lost (acres)	1,850	1,600
Bottom protected (acres)	3,371	8,080
Total cost (US$)	6,000,000	1,985,000

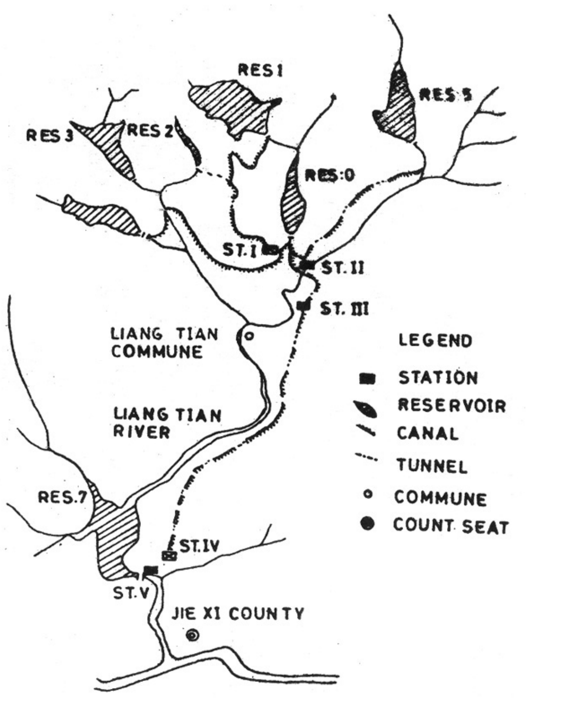

Figure 10. Multi-purpose cascade development scheme in which small rivers, rivulets and streams are utilized for storing water (after Naibo[30]).

spot above the Station One. The collective contributions from several reservoirs provide required discharge and water balance to run the power plant of Station One. Downstream a few more hydroelectric power plants are constructed on spots where the requirements of water balance are met.

Each of these stations has the capacity of generating 6–12 MW of electricity. Thus, 4 or 5 smaller micro-hydel power plants provide electricity enough to meet the needs of the region and also feed the regional or national grid.

The reservoir in the lower reaches of the rivulet can have substantial storage to supply water for drinking and irrigation locally as well as regionally.

The Cascade Development Schemes requires less investments, the periods of construction are shorter, and the benefits come quite early[30]. Moreover, the projects can be executed locally and thus local people can participate meaningfully in the ventures.

Economics of smaller dams

As stated above, smaller dams cost much less, start giving benefits quite early, bring greater benefits to the people, including the local communities, and cause less damage to natural resources such as minerals, forests, agricultural lands, and to the habitats and socio-economic fabric of the people affected[28,29].

The data on major and minor irrigation projects entailing construction of dams in India collected by the Planning Commission were subjected to cost-benefit analysis[31]. Table 7 eloquently demonstrates that it is better to go for many smaller dams than for big dams, whether for water storage or for power generation. This is true not only for India; it was also true for USA as early as the 1950s. A comparison of benefits of a big dam with a series of much smaller dams located in the tributaries of the same river (Table 8) showed that the latter not only cost less but start giving benefits quicker and without impairing the environment[32].

There is no denying that the cost of the electricity generated from smaller projects would be high (as much as two times). However, if one takes into consideration (i) the monetary value of the natural resources (mineral, forest, agricultural land) that are lost, (ii) the cost of restoring the damaged land, and (iii) the huge financial burden on relocating and rehabilitating the uprooted/displaced people, the high cost of electricity generated by smaller hydel projects is more than compensated[28,29]. The well-being and socio-economic security of the people should be the overriding consideration, not the cost. It should also include the communities adversely affected by dam-building activities.

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Received 7 January 2014; revised accepted 11 April 2014