Geological, lineament and landslide studies of the reservoir and its vicinity of Bunakha hydroelectric project, Bhutan Himalaya

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Abstract

Lineament, landslide inventory and mapping of geological formation for the reservoir area of Bunakha hydroelectric project was carried out by input of remote sensing and field studies. Geological map of the area was prepared from published literature and Author's traverses. The rocks belong to Central Crystalline belt of Bhutan Himalaya comprising Thimphu Gneissic Complex and Paro Formation. The area is traversed by series of lineaments; which have four major trends having distinct structural relationship with N-S trending antiform. In reservoir area 96 lineaments (L-1 to L-128) were identified from the images and most of the lineaments which are falling in the reservoir area were checked in the field. Lineaments are structural discontinuities and are often conduits for the release of energy accumulating in an area as earthquake. Deep lineaments control the seismicity in an area. Total 51 landslides were identified from the reservoir and its vicinity. The objectives of the studies were to provide the base maps for the assessment of their impact on project structures and reservoirs areas. These studies will also be useful for forecasting of slope stability in the event of reservoir filling and later fluctuation.

1. Introduction:

For a careful evaluation of major river valley projects, precise geological, major lineament / fault pattern and landslide inventory maps of reservoir/catchment area are required as input maps to ascertain the feasibility of construction of dam and other appurtenant structures and also for the stability of reservoir. A well searched and studied, dam site is likely to provide a long term safety for the river valley projects. Remote Sensing and Geographical Information System (GIS) are used which are important tools for delineating the topography, shape of the valley, size of the catchments, likely river discharge, amount of storage capacity, erosion and hazard assessment, geomorphology, Quaternary geology, type of rocks in any inaccessible area and delineation of major structural elements in the detailed project stage investigations. The tectonic fabric of an area is inferred from the alignment of linear fracture zones/faults/shear zones which are seen as lineaments in the satellite imagery.

The present work was carried out for the reservoir area of Bunakha hydroelectric project, to map geological formations, landslide inventory and lineaments with input of remote sensing and field studies. The reservoir impounded by Bunakha dam is bounded between latitude N27°07’57” to N27°15’52” and longitude E89°30’57.364” to E89°32’41.891”, would be spread in 6.82 sq km area (at FRL 2006m) with a length (linear) of 17.25 km has been studied. This area receives high monsoon precipitation in the form of rainfall and due to rugged terrain rain-water flows along the river into the Bay of Bengal. The stability of this area depends on the combined effect of lithology, slope, structures, land use & land cover and hydro-geological condition. The reservoir would be formed as linear bay except 700m wide spread near village Bunakha in a declivity occupied by talus wash / drift material and river terrace deposits.

Indian Remote Sensing Satellite data Cartosat–I, dated 2nd January 2010, sensor PAN Force (Max ±26°) & Aft (Max ±5°), spectral band width 0.50–0.85 µm (Pan) having the resolution of 2.5m was used to identify and delineate structural and drainage features and for the preparation of landslide inventory, lineament and drainage maps of the reservoir area. For the image processing ERDAS Imagine 9.3 was used and for the digitization and analysis Arc GIS 9.3 was used. The higher versions of Workstation computers were used for the image processing. Landslide inventory with lineaments and drainage map was generated on 1:10,000 scale with the help of topomaps and Cartosat imagery, while the geological map of the project reservoir area was generated from published literature and author’s traverses. Ground features available on the topomaps on 1:50,000 scale have been used on the base map for facilitating quick ground referencing.

Most of the geomorphic features present in the project area are the result of polycyclic endogenic and exogenic processes of varying intensities through times. River Wang Chhu is drained by its three major tributaries namely Thimphu Chhu, Paro Chhu and Ha Chhu. It seems that the drainage of the area is still in its mature stage, which is mainly controlled by lithology, structure and tectonics. Higher order streams have both tectonic and lithological control while lower order streams have developed on the neo-tectonic uplifts etc. Geomorphologically, project area is characterized by deep, steep and narrow valleys with long convex slopes descending from the ridgeline ending in near vertical and steeply convex gorges or V-shaped valley.

2. Geological Setting of the Reservoir Area:

The rocks of the Bunakha hydroelectric project reservoir area are falling under the Central Crystalline belt of Bhutan Himalaya trending in E-W direction (Figure 1). The Central Crystalline consists of Thimphu Gneissic Complex and Paro Formations and MCT-I forming the contact between these two Formations in the reservoir area (GSI, 1979-80 and Koike, 2001, 2002)]. In the catchment area the Paro Formation is a lenticular shape separated from upper high-grade metamorphosed migmatitic gneisses by thrust and low grade gneisses with gradational contact. The bedrock encountered at the proposed dam site at Bunakha and its appurtenant structures is represented largely by crystalline rocks of Thimphu Gneissic Complex belonging to upper amphibolite facies of metamorphism. These litho-units are characterized by heterogeneous lithology consisting of foliated gneisses, streaky and banded gneisses, amphibolite gneisses with large boudins and bands of quartzite and thin interlayer of mica schists/foliated gneisses with large porphyroblasts of garnet and bands of calc-silicate gneisses (Naithani et.al. 2011).

Moreover major part of the area especially the right bank of Wangchhu is covered with thick vegetation, which has hampered the identification of different types of rocks. In the catchment area Thimphu Formation consists of a litho-assemblage of para-gneisses and migmatites with field discernible units of boudinaged biotite-gneiss, banded and streaky gneisses, garnetiferous psammitic schists and gneisses with large boudins and stretched bands of quartzite. Gneisses are interlayered with garnetiferous quartz-mica schist where garnet constitutes as much as 3% of mineral assemblage. The crystalline rocks overlain by the Paro Formation near Ha town (Gokul et.al., 1976) continues towards southeast and could be seen at Betekha village along Chozom-Ha road section, where the metasediments of the Paro Formation are grading into the succession of garnet mica schist, psammitic gneiss, calc-gneiss, augen gneiss and granite gneiss dipping towards NE to ENE. Towards south, across Ha Chhu – Chapcha anticlinal fold, the crystalline units are again grading into metasedimentary sequence comprising banded quartzite, garnet mica schist and a few crystalline limestone bands interleaving a transitional zone. Granite gneisses are exposed by conspicuous domical structure at Chuzom, designated as Sisina Formation by Jangpangi (1980). The Sisina Formation is overlain by Paro metasediments with a transitional zone comprising garnet mica schists and gneisses. Structurally the Sisina Formation is a "tectonic window" of the underlying crystalline units, which is exposed by erosion of Wang Chhu valley.

The calcareous dominating unit of Paro formation extends in Jangtelumchhu-Chapacha-Lungshaka-Thamchu sections on the left bank and Wangnakha-Teshakha area of the right bank of Wangchhu River. In terms of regional perspectives, there are several intercalations of marble, crystalline limestone and bands of calc-silicate rocks within Paro Formation, at places these attain calc-granulitic/ calc-gneissic character. The quartzite with thin partings of schist is well exposed in the middle reaches of Jagntelamchhu and Tanalumchu sections and in Bunakha area approximately 2.0 km u/s from the dam axis.

The dam site is located on the rocks of Thimphu Formation and initial reaches of Bunakha reservoir for a distance of 1.6 km would spread over para-gneisses with field discernible units of boudinaged, biotite-gneisses, banded and streaky gneisses, psammitic schist and gneisses with large boudins and stretched bands of quartzites. Further upstream i.e. up to Eulkha, the reservoir would be on the rocks of Paro Formation. Initial reach from 1.6 km to 3 km upstream the reservoir area consists of flaggy, well bedded quartzite, micaceous quartzite with interbands of limestone and thin layers of graphitic schist. In the northern part more calcareous intercalations transformed into calc-granulites are exposed. From 3 km to 9.5 km calcareous unit containing marble bands and amphibolite gneisses are exposed. From 9.5 km and up to Eulkha, garnetiferous quartz mica schist, graphite schist and calc silicate gneisses with bands of quartzite and metabasics are present. In the Chuzom area granite gneisses and garnet mica schists are exposed.

The composite picture of folding in this part of Bhutan Himalaya is complex because of superimposition of three generations of folds viz. F1, F2 and F3. The earlier folds are present in the Thimphu and Paro Formations and are generally E-W trending, tight to isoclinal with large amplitude to wave length ratio; these commonly attain reclined geometry. During progressive deformation, at places, these folds are highly appressed, particularly in the vicinity of high strain zone, where adjoining fold limbs become inseparable. Endemic to folding these litho-units are traversed by multiple set of discontinuities viz. (i) parallel to axial plane forming valley parallel longitudinal joints (ii) steeply dipping conjugate system of diagonal joints and (iii) low angle conjugate discontinuities. In addition to these discontinuities, foliation discontinuities and shear-zones parallel to foliation have also been recorded. The major antiform (fold phase F2 & F3) has been reported in the project area extending from confluence of Dudullungpa Chhu with Wang Chhu up to Bunakha by Geological Survey of India (1979-80) and Wang Chhu is flowing along this anticlinal axis (Bharagava and Dasgupta, 1995). At the dam site the rocks are dipping in opposite direction on both banks and the river Wang Chhu flows along the N-S trending axial zone of southerly plunging antiformal structure.

3. Lineament Study:

A preliminary examination of the image reveals several instances of tonal variations along a linear feature and/or discordant relationship of the rocks with the host rocks of the region, suggesting the presence of various lineaments. The observed lineaments can be classified into five categories: drainage, joints, depression, contact zones and unclassified lineaments. Most of the lineaments are reflected on images as tonal/vegetation linears. The area is traversed by series of lineaments; which have following trends having distinct structural relationship with N-S trending antiform:

i) N-S, axis parallel longitudinal lineaments.
ii) NW-SE, diagonal lineaments
iii) NE-SW, diagonal lineaments
iv) E-W, trending transverse lineaments (parallel to fold axis of second generation)

In the study area 96 lineaments were identified from the images and most of the lineaments which are falling in the reservoir area were checked in the field and the details are given in Table 1. These lineaments show alignment of drainage, depression, ridge etc (Figure 2). Though, all the lineaments could not be confirmed in the field, some of these have clear manifestation as line of structural disturbances.

In general the lineaments are the reflection of the mega and major joints, faults and fractures. Based on the strike length, lineaments of this area are classified into three types viz. mega (length >1500 m), major (500 – 1500 m) and minor (<500 m) lineaments. The area around mega lineaments should be studied in detailed for slope stability point of view, because they have the role for landslide activity. The area close to the mega lineament is more vulnerable for landslide activity, because intensity of fracturing / shearing is more in that area and weathering will be deep.

4. Landslide Study:

Landside inventory of the reservoir area was prepared on 1:10000 scale with the input from remote sensing and field studies (Figure 2). Landslides in the area were classified based on status of activity (active, old/ dormant/ stabilized), material involved (debris avalanches, rock-slide etc.), morphometric character and scale. Based on crown height, landslide are classified into three types viz. large (crown height >10 m), medium (5-10 m) and minor (< 5 m).

Few studies dealing with landslides have been conducted in Bhutan affirmed that failures are related to lithology, trigger and human activity (Kuenza et.al. 2004). Few studies of land sliding in Bhutan have been quantitative in nature, through inferences can be drawn from study of the soil cover of Bhutan as logged in detailed by Baillie et.al. (2004). Catchment area of Bunakha HEP suffer from deep (>8 m) levels of weathering, much of which has often been stripped by intermittent mass movements and deposited as thick mantle of colluvium ranging from 50 cm to over 2 m in depth interlayered with buried soils. In this area, along the road section the number of landslides are increasing in susceptible areas through ground disturbance, particularly road cuttings using previous methods of construction or design such as blasting and / over-steep cutting in weak rock.

Debris flows are active in the upper part of the catchment area. Deposits are mainly confined to first order drainage lines with source regions on the upper valley sides, with no open slopes found. The steep valley morphology resulted in the terminus of debris-flow deposits rarely being found. The debris flows maintain high connectivity to second order or higher streams. The source material for debris flows is generally pre-existing colluvium or first time failure at stream headwater, topographic hollows, stream banks or road cuttings where vegetation has been stripped. Source slip planes are preferentially located at breaks in weathering grade in both colluvium and also bedrock that is often weathered to residual soil.

Rock slides were predominantly observed at road cuttings. Otherwise such features are difficult to observe under the heavily forested natural slopes with colluvium concealing near-surface structure. However, recent bedrock failures at road level, where bedrock is exposed, are often associated with natural topographic depressions or spurs. Deformed tree growth upslope of recent failures are interpreted to predate road construction and suggest age's pre-construction in many cases.

Although individual rock falls may seem minor events, collectively they make an important volumetric contribution to slope erosion (Rosser et al., 2005). Rock fall occur on a daily basis along the cut slopes, with observed volumes ranging from a few centimeters cubed to several tens of centimeters, usually defined by local joint spacing and structural controls. Rare, large, well weathered blocks in excess of 10 m^3 were discovered on valley sides and within stream beds and could be closely associated with major fault traces, seismic triggering is a justifiable interpretation for their origin based on the recorded seismicity of the area and inferred past seismicity.

In the study area 51 landslides were identified from the images and most of the landslides were checked in the field and the details are given in Table 2. Some of the landslides area either totally submerged or upstream of reservoir area or their toe lies much above the Full Reservoir Level (2006) but the landslide numbers 5, 6, 19, 24, 25 and 50 would be partially submerged in the reservoir and need to be considered as potential slope instability zones. Landslide number 5 and 6 are located on the left bank of Wang Chhu just u/s of confluence with Tanalum Chhu. 17m high and 23m wide, landslide number 19 is located on the right bank of Wang Chhu, at the confluence of first order drainage with Wang Chhu i.e. u/s of village Wanakha and area around this landslide is sparsely vegetated. 35m high and 45m wide, landslide number 24 is located on the right bank of Wang Chhu, just u/s from the confluence with Tham Chhu and area around the landslide is sparsely vegetated. 13m high and 23m wide landslide number 25 is located at right bank of Wang Chhu i.e. 375 m u/s from landslide number 24 and the area around the landslide is sparsely vegetated. Landslide number 50 is located at the right bank of Wang Chhu i.e. 300 m u/s from the dam axis and area is densely vegetated. In the event of reservoir filling and later fluctuation, these areas should be investigated from the slope stability of reservoir rim point of view.

5. Discussion and Conclusions:

Broadly, the land use pattern of the area are grouped into five categories: agricultural land/ populated flat land, thickly vegetated forest area, moderately vegetated forest area, open scrub area with lesser ground cover and barren land. More than 50.83 percent of the area comes under the thickly vegetated forest followed by moderately vegetated forest area (22.55%), agricultural / populated flat land (11.67%), open scrub area (9.27%) and barren land (3.42%). In the Bunakha HEP area about 79% of the population's main source of livelihood is agriculture (Naithani et.al. 2011). For the reservoir, total about 6.82 sq km land will be required, and the area comprises agricultural land including orchards, forest area, water bodies and barren rocky outcrop. No village, no road and no archaeological monument are coming under submergence zone of the reservoir area. There is no nature reserve and wildlife conservation area near the project site. No historical or cultural monument will be lost due to project activities. Development of tourism will be quite feasible here once the reservoir is under operation. Phuentsholing – Thimphu bypass is above the reservoir rim area will be a great tourist attraction.

The Wang Chhu river system is mostly affluent with ground water feeding to the river with little or no scope for reversal of ground water gradient on reservoir impoundment. Thus the reservoir competency vis-à-vis across the high rise water divides through joints or solution channels in calcareous intercalations to adjoining valleys of Sankosh and Torsa river system was ruled out.

The Bunakha reservoir at proposed FRL of 2006 m would impound 329.16 Mcum of water spreading over an area of 6.82 sq km. Because of the steep gradient of the river (1:100 m) the reservoir extends only for a short distance of 17.25 kms in the upstream, up to foot hill of the Dorbi Dzong. Arms of the reservoir would also extend along Ha Chhu (for 2.5 kms) and would encroach other tributaries viz. Sirupa Chhu, Jangtulam Chhu, Tanalum Chhu and Thamchhu. In most of the reaches the reservoir would remain contained with a steep valley gorge.

Geology map of the reservoir area will be helpful for the reservoir rim stability analysis because in the mountainous terrain lithology is one of the major causative factors for slope instability. Landslides are influenced by geological structures which include primary and secondary discontinuity in the rocks such as bedding planes, joints, foliations, faults and thrusts. In case of soil material and overburden the landslide activity depends upon the genesis, nature, depth and age of the material. So, these factors should also be taken into consideration for the stability analysis.

The linear bay of proposed Bunakha reservoir is generally margined with steep rocky slopes excepting immediately upstream of the dam site around village Bunakha (incidentally forming 30% of the reservoir capacity) where valley opens up with a prominent declivity and the reservoir has a maximum width of the order of 700 m. This area is containing drift material showing signature of creep. The material with poor shear strength may yield to rotational slope failure or debris slide on imposition of partial submerged condition, especially on fast depletion of lake and superposed seismic loading. Hence, this area needs to be checked for stability.

Fluctuation between FRL (2006m) and MDDL (1950m) may induce land deformation at various slopes of reservoir rim mainly because of the geometry of discontinuities with inclination of natural slope. The sections where stability need to be checked incorporating slope geometry, mechanical properties of material, submerged slope conditions and seismic factor are identified as landslide numbers 5, 6, 19, 24, 25 and 50 marked in figure 2.

The steep slopes overlooking the reservoir are dotted with moraine drift / talus scree, these are likely to have low seismic rigidity and may cause increase in seismic intensity in event of earthquake. Large numbers of dormant / stable landslides are present in the catchment area, which may reactivate in the event of earthquake or cloudburst. High silt yield in the reservoir is apprehended because of these factors.

Lineament numbers 19 and 64 should be studies from the slope stability point of view. Lineament 19, marked along the Tanalum Chhu, has been marked as suspected fault based on geomorphological anomalies. Lineaments (L113 to L116, L119, L124 & L125) which have been identified along the Wangchhu river, and falling within the reservoir area should be studied from the reservoir competency point of view. Embayment of N-S/NE-SW lineaments and their intersections with other lineaments could be probable points of future seismic activity in the area. Hence, these lineaments should be considered for seismotectonic evaluation, array of micro-earthquake stations may be established to monitor their seismic activity.

Table 1
Description of lineaments of Bunakha HEP Reservoir Area

Lineament No	Longitude	Latitude	Length in m	Type	Orientation	Status	Location
L1	89°32'24.261"E to 89°32'36.119E	27°8'8.705''N to 27°7'55.844''N	515	Major	Northwest-southeast	Controlled by depression	130m u/s of dam axis, crossing river and traversing towards RB.
L2	89°32'30.679"E to 89°32'36.108E	27°8'21.647''N to 27°8'23.568''N	162	Minor	ENE-WSW	Controlled by depression	Left bank, falling in reservoir area.
L3	89°32'19.974"E to 89°32'23.584E	27°8'36.462''N to 27°8'38.493''N	117	Minor	Northeast-southwest	Controlled by depression	Left bank of reservoir, falling in reservoir area.
L4	89°32'6.457"E to 89°32'9.692E	27°8'50.907''N to 27°8'52.242''N	98	Minor	ENE-WSW	Controlled by 1st order drainage	RB of reservoir, partially falling in reservoir area.
L5	89°31'49.636"E to 89°32'6.575E	27°8'50.705''N to 27°8'55.844''N	674	Major	Northwest-southeast	Controlled by depression	Major portion of lineament in reservoir area crossing the river.
L6	89°32'11.164''E to 89°32'18.999''E	27°9'11.903"N to 27°9'8.11''N	246	Minor	Northwest-southeast	Controlled by drainage	Right bank of reservoir, falling in reservoir area.
L7	89°31'57.098''E to 89°32'2.719''E	27°9'13.461"N to 27°9'14.645''N	158	Minor	ENE-WSW	Controlled by drainage	R/B of reservoir, partially falling in reservoir area.
L8	89°32'3.328"E to 89°32'10.528''E	27°9'32.727"N to 27°9'29.117''N	228	Minor	Northwest-southeast	Controlled by drainage	R/B of reservoir, major portion is falling in reservoir area.
L9	89°32'3.559"E to 89°32'6.59''E	27°9'37.0832"N to 27°9'35.217''N	100	Minor	Northwest-southeast	Controlled by depression	R/B of reservoir, partially falling in reservoir area.
L10	89°32'12.745''E to 89°32'18.151''E	27°9'38.327"N to 27°9'36.344''N	161	Minor	Northwest-southeast	Controlled by drainage	Left bank of reservoir, falling in reservoir area.
L11	89°32'4.87''E to 89°32'12.005''E	27°9'53.682"N to 27°9'53.311''N	202	Minor	WNW-ESE	Controlled by ridge	R/B of reservoir, partially falling in reservoir area.
L12	89°32'1.861'' E to 89°32'6.58''E	27°9'57.546"N to 27°10'2.563''N	198	Minor	Northeast-southwest	Controlled by ridge	R/B of reservoir, partially falling in reservoir area.
L13	89°32'0.608''E to 89°10'3.286''E	27°10'5.585"N to 27°10'3.286''N	159	Minor	Northwest-southeast	Controlled by drainage	Right bank of reservoir, falling in reservoir area.
L14	89°32'2.35''E to 89°32'4.395''E	27°10'28.05"N to 27°10'29.66''N	75	Minor	Northeast-southwest	Controlled by depression	Left bank of reservoir, partially falling in reservoir area.
L15	89°32'1.248" E to 89°32'2.959''E	27°10'28.449"N to 27°10'30.92''N	89	Minor	Northeast-southwest	Controlled by depression	Left bank of reservoir, falling in reservoir area.
L16	89°31'59.566''E to 89°32'1.871''E	27°10'30.537"N to 27°10'32.62''N	92	Minor	Northeast-southwest	Controlled by depression	Left bank of reservoir, partially falling in reservoir area.

L17	89°31'54.018''E to 89°31'56.312''E	27°10'44.721"N to 27°10'94.68''N	63	Minor	ESE-WNW	Controlled by depression	Left bank of reservoir, falling in reservoir area.
L18	89°31'15.369"E to 89°31'18.553''E	27°12'29.629"N to 27°12'31.19''N	101	Minor	Northeast-southwest	Controlled by drainage	Left bank of reservoir, falling in reservoir area.
L19	89°31'54.699''E to 89°31'57.286''E	27°10'58.564"N to 27°11'5.609''N	233	Minor	Northeast-southwest	Controlled by drainage (Tanalum Chhu), suspected fault? Geomorphological anomalies.	Left bank of reservoir, falling in reservoir area.
L20	89°31'40.969''E to 89°31'42.556''E	27°10'58.869"N to 27°11'1.887''N	103	Minor	Northeast-southwest	Controlled by drainage	Left bank of reservoir, falling in reservoir area.
L21	89°31'31.329''E to 89°31'31.838''E	27°11'2.641"N to 27°11'4.52''N	59	Minor	Northeast-southwest	Controlled by depression	Left bank of reservoir, partially falling in reservoir area.
L22	89°31'24.46''E to 89°31'26.066''E	27°11'1.044"N to 27°11' 3.85''N	97	Minor	Northeast-southwest	Controlled by depression	Right bank of reservoir, falling in reservoir area.
L23	89°31'21.54''E to 89°31'26.804''E	27°11'8.653"N to 27°11'16.73''N	290	Minor	Northeast-southwest	Controlled by drainage	Left bank of reservoir, partially falling in reservoir area.
L24	89°31'4.45''E to 89°31'6.116''E	27°11'11.79"N to 27°11'13.78''N	77	Minor	Northeast-southwest	Controlled by depression	R/B of reservoir, major part is falling in reservoir area.
L25	89°30'36.686''E to 89°30'41.916"E	27°11'23.68"N to 27°11'23.29''N	144	Minor	ESE-WNW	Controlled by drainage	Along the Ha Chhu, falling in reservoir area.
L26	89°31'31.078''E to 89°31'33.669"E	27°12'8.455"N to 27°12'10.42''N	93	Minor	Northeast-southwest	Controlled by drainage	Left bank of reservoir, partially falling in reservoir area.
L27	89°31'12.388''E to 89°31'14.584''E	27°12'24.908"N to 27°12'27.10''N	91	Minor	Northeast-southwest	Controlled by drainage	Right bank of reservoir, falling in reservoir area.
L28	89°31'12.184''E to 89°31'14.741''E	27°12'30.586"N to 27°12'27.81''N	111	Minor	Northwest-southeast	Controlled by drainage	Right bank of reservoir, falling in reservoir area.
L29	89°31'6.734"E to 89°31'10.199''E	27°12'54.852"N to 27°12'27.81''N	138	Minor	Northwest-southeast	Controlled by depression	Right bank of reservoir, falling in reservoir area.
L30	89°31'6.91"E to 89°31'11.697"E	27°13'39.43"N to 27°13'41.17''N	142	Minor	Northeast-southwest	Controlled by drainage	Right bank of reservoir, falling in reservoir area.
L31	89°31'13.81''E to 89°31'21.548''E	27°14'3.01"N to 27°13'59.61''N	237	Minor	Northwest-southeast	Controlled by drainage	R/B of reservoir, partially falling in reservoir area.
L32	89°31'28.549''E to 89°31'35.046''E	27°14'12.43"N to 27°14'11.10 ''N	184	Minor	ESE-WNW	Controlled by drainage	Left bank of reservoir, partially falling in reservoir area.

L33	89°31'27.938''E to 89°31'34.127''E	27°14'28.405"N to 27°14'27''N	175	Minor	ESE-WNW	Controlled by drainage	R/B of reservoir, partially falling in reservoir area.
L34	89°31'34.307''E to 89°31'42.105''E	27°14'56.013"N to 27°14'56.27''N	215	Minor	East-west	Controlled by drainage	R/B of reservoir, partially falling in reservoir area.
L35	89°31'43.383''E to 89°31'47.109''E	27°15'20.72"N to 27°15'18.57''N	120	Minor	Northwest-southeast	Controlled by depression	R/B of reservoir, partially falling in reservoir area.
L36	89°31'43.898''E to 89°32'2.719''E	27°9'14.645"N to 27°9'5.725''N	819	Major	Northeast-southwest	Controlled by drainage	R/B of reservoir, partially falling in reservoir area.
L37	89°31'51.119''E to 89°32'18.939''E	27°9'9.606"N to 27°8'51.848''N	943	Major	Northwest-southeast	Controlled by depression	R/B of reservoir, partially falling in reservoir area.
L38	89°30'37.932''E to 89°31'22.972''E	27°9'47.815"N to 27°10'10.96''N	1441	Major	Northeast-southwest	Controlled by drainage	R/B of reservoir, outside of reservoir area.
L39	89°31'25.28"E to 89°32'7.308"E	27°10'11.148"N to 27°10'1.887''N	1191	Major	ESE-WNW	Controlled by drainage	R/B of reservoir, partially falling in reservoir area.
L41	89°33'9.602''E to 89°33'44.142''E	27°1' 58.869"N to 27°11'12. 46''N	1196	Major	Northeast-southwest	Controlled by drainage	L/B of reservoir, outside of reservoir area.
L43	89°30'14.713''E to 89°31'8.781''E	27°15'4.648"N to 27°15'0.633''N	1442	Major	ESE-WNW	Controlled by drainage	Right bank of reservoir, outside of reservoir area.
L47	89°31'16.885''E to 89°32'24.741"E	27°18'15.338"N to 27°18'11.16''N	1880	Mega	East-west	Controlled by drainage	Right bank of reservoir, outside of reservoir area.
L53	89°31'49.311"E to 89°32'7.62"E	27°19'7.25"N to 27°19'18.492"N	606	Major	Northeast-southwest	Controlled by drainage	Right bank of reservoir, outside of reservoir area.
L55	89°32'35.887"E to 89°33'0.942"E	27°19'1.468"N to 27°18'52.474"N	749	Major	Northwest-southeast	Controlled by drainage *Paro Chhu*	Upstream of reservoir, outside of reservoir area.
L56	89°33'1.745"E to 89°33'18.93"E	27°18'51.992"N to 27°19'5.483"N	620	Major	Northeast-southwest	Controlled by drainage *Wangchhu*	Upstream of reservoir, outside of reservoir area.
L59	89°33'0.392"E to 89°34'1.18"E	27°17'34.676"N to 27°17'48.245"N	1711	Mega	Northeast-southwest	Controlled by depression	Left bank of Wangchhu, outside of reservoir area.
L60	89°33'19.026"E to 89°34'26.689"E	27°17'0.845"N to 27°16'6.209"N	2496	Mega	Northwest-southeast	Controlled by drainage	Left bank of Wangchhu, outside of reservoir area.
L61	89°32'44.109"E to 89°33'31.148"E	27°16'44.201"N to 27°16'13.807"N	1599	Mega	Northwest-southeast	Controlled by drainage	Left bank of Wangchhu, outside of reservoir area.
L62	89°33'24.611"E to 89°34'5.752"E	27°18'2.894"N to 27°18'10.212"N	1148	Mega	Northeast-southwest	Controlled by drainage	Left bank of Wangchhu, outside of reservoir area.
L63	89°31'53.665"E to 89°33'16.164"E	27°14'3.596"N to 27°13'58.702"N	2266	Major	East-west	Controlled by drainage *Thamchhu*	Left bank of reservoir, outside of reservoir area.

L64	89°33'3.778"E to 89°32'58.329"E	27°9'52.161"N to 27°11'16.916"N	2610	Mega	NNW-SSE	Intersect. of drainage, geomorp. control	Left bank of reservoir, outside of reservoir area.
L66	89°33'25.572"E to 89°34'29.743"E	27°13'57.344"N to 27°13'18.599"N	2148	Mega	Northwest-southeast	Controlled by drainage	Left bank of reservoir, outside of reservoir area.
L67	89°29'4.649"E to 89°29'54.291"E	27°14'10.663"N to 27°13'56.739"N	1424	Major	Northwest-southeast	Controlled by drainage	Right bank of reservoir, outside of reservoir area.
L68	89°30'2.766"E to 89°30'52.408"E	27°13'51.29"N to 27°13'39.182"N	1463	Major	Northwest-southeast	Controlled by drainage	Right bank of reservoir, outside of reservoir area.
L69	89°29'41.578"E to 89°30'8.82"E	27°12'54.989"N to 27°12'54.384"N	723	Major	East-west	Controlled by drainage	Right bank of reservoir, outside of reservoir area.
L70	89°30'19.717"E to 89°30'53.013"E	27°12'57.411"N to 27°12'53.173"N	948	Major	WNW-ESE	Controlled by drainage	Right bank of reservoir, outside of reservoir area.
L71	89°31'12.991"E to 89°31'34.785"E	27°12'59.227"N to 27°13'2.254"N	718	Major	ENE-WSW	Controlled by drainage	Left bank of reservoir, outside of reservoir area.
L73	89°33'47.366"E to 89°34'26.716"E	27°14'11.268"N to 27°14'41.538"N	1422	Major	Northeast-southwest	Controlled by drainage	Left bank of reservoir, outside of reservoir area.
L77	89°33'25.175"E to 89°33'48.681"E	27°8'24.631"N to 27°8'19.875"N	690	Major	ESE-WNW	Controlled by drainage *SirupaChhu*	Left bank of reservoir, outside of reservoir area.
L78	89°33'0.113"E to 89°33'28.438"E	27°10'58.492"N to 27°10'37.11"N	1026	Major	Northwest-southeast	Controlled by drainage	Left bank of reservoir, outside of reservoir area.
L79	89°34'16.319"E to 89°34'36.864"E	27°19'3.015"N to 27°18'46.3"N	777	Major	Northwest-southeast	Controlled by drainage	Along Geynitsang Chhu, outside of reservoir area.
L80	89°33'47.593"E to 89°34'15.445"E	27°12'11.936"N to 27°12'36.87"N	1087	Major	Northeast-southwest	Controlled by drainage	Left bank of reservoir, outside of reservoir area.
L81	89°33'40.405"E to 89°34'14.668"E	27°15'50.799"N to 27°16'3.177"N	1019	Major	Northeast-southwest	Controlled by depression	Left bank of Wangcchu, outside of reservoir area.
L84	89°33'46.711"E to 89°34'3.943"E	27°16'57.685"N to 27°17'5.843"N	535	Major	Northeast-southwest	Controlled by drainage	Left bank ofWangchhu, outside of reservoir area.
L85	89°33'38.914"E to 89°34'20.022"E	27°15'49.996"N to 27°15'39.979"N	1188	Major	Northwest-southeast	Controlled by drainage	Left bank of reservoir, outside of reservoir area.
L86	89°32'6.575"E to 89°32'30.165"E	27°15'8.861"N to 27°15'5.419"N	659	Major	East-west	Controlled by drainage	Left bank of reservoir, outside of reservoir area.
L87	89°33'9.767"E to 89°33'30.538"E	27°17'24.15"N to 27°17'20.842"N	584	Major	ESE-WNW	Controlled by drainage	Left bank of Wangchhu, outside of reservoir area.
L88	89°33'10.199"E to 89°33'43.779"E	27°8'17.378"N to 27°8'34.343"N	1073	Major	Northeast-southwest	Controlled by drainage *SirupaChhu*	Left bank of reservoir, outside of reservoir area.

L89	89°31'24.752"E to 89°31'48.223"E	27°17'54.768"N to 27°18'1.418"N	676	Major	Northeast-southwest	Controlled by drainage	Right bank of Wangchhu, outside of reservoir area.
L91	89°31'15.278"E to 89°31'34.783"E	27°19'5.428"N to 27°19'27.1"N	874	Major	Northeast-southwest	Controlled by drainage	Right bank of Paro Chhu, outside of reservoir area.
L92	89°33'6.863"E to 89°33'29.868"E	27°9'47.227"N to 27°9'39.22"N	687	Major	Northwest-southeast	Controlled by drainage (Jangtulam Chhu)	Along the Jangtulam Chhu, outside of reservoir area.
L93	89°31'49.636"E to 89°32'1.688"E	27°12'17.881"N to 27°12'47.216"N	922	Major	Northeast-southwest	Controlled by drainage	Left bank of reservoir, outside of reservoir area.
L94	89°32'26.701"E to 89°32'41.568"E	27°18'10.596"N to 27°18'4.019"N	461	Minor	Northwest-southeast	Controlled by drainage	Right bank of Wangchhu, outside of reservoir area.
L95	89°31'16.29"E to 89°31'22.665"E	27°12'30.423"N to 27°12'33.265"N	208	Minor	Northeast-southwest	Controlled by drainage	Left bank of reservoir, partially fall in the reservoir rim area.
L96	89°34'12.638"E to 89°34'28.189"E	27°11'11.547"N to 27°11'5.082"N	478	Minor	Northwest-southeast	Controlled by drainage (Tanalum Chhu)	Along the Tanalum Chhu, outside of reservoir area.
L97	89°31'17.37"E to 89°31'44.137"E	27°16'1.267"N to 27°16'0.953"N	744	Major	East-west	Controlled by drainage (Churalung pa Chhu)	Along the Churalungpa Chhu, outside of reservoir area.
L98	89°31'0.232"E to 89°31'16.152"E	27°14'15.858"N to 27°14'22.083"N	485	Minor	Northeast-southwest	Controlled by depression	Right bank of reservoir, outside of reservoir area.
L99	89°30'48.916"E to 89°31'6.374"E	27°12'2.425"N to 27°12'13.389"N	588	Major	Northeast-southwest	Controlled by drainage	Right bank of reservoir, outside of reservoir area.
L102	89°30'19.872"E to 89°30'34.264"E	27°10'57.335"N to 27°11'18.324"N	761	Major	Northeast-southwest	Controlled by drainage	Right bank of Ha Chhu, outside of reservoir area.
L104	89°30'58.689"E to 89°31'9.904"E	27°10'52.929"N to27°11'4.697"N	487	Major	Northeast-southwest	Controlled by drainage	Right bank of reservoir, outside of reservoir area.
L106	89°32'4.151"E to 89°32'30.067"E	27°12'12.063"N to 27°12'7.312"N	755	Major	ESE-WNW	Controlled by drainage	Left bank of reservoir, outside of reservoir area.
L109	89°31'17.258"E to 89°31'25.964"E	27°14'31.454"N to 27°14'29.523"N	250	Minor	WNW-ESE	Controlled by drainage	Right bank of reservoir, outside of reservoir area.
L110	89°32'51.814"E to 89°32'55.398"E	27°13'29.669"N to 27°13'56.076"N	832	Major	NNE-SSW	Controlled by drainage	Left bank of Tham Chhu, outside of reservoir area.
L111	89°33'6.633"E to 89°33'16.653"E	27°18'10.888"N to 27°18'2.007"N	382	Minor	Northwest-southeast	Controlled by drainage	Left bank of Wangchhu, outside of reservoir area.
L112	89°31'25.8"E to 89°31'43.898"E	27°18'46.827"N to 27°19'6.316"N	790	Major	Northeast-southwest	Controlled by drainage	Right bank of Paro Chhu, outside of reservoir area.

L113	89°31'26.094"E to 89°31'43.687"E	27°10'55.121"N to 27°10'48.23"N	571	Major	NNW-SSE	Controlled by drainage *Wangchhu*	Along the Wangchhu river, fall in the reservoir area.
L114	89°32'25.993"E to 89°32'19.74"E	27°8'27.788"N to 27°8'35.634"N	306	Minor	NNW-SSE	Controlled by drainage *Wangchhu*	Along the Wangchhu river, fall in the reservoir area.
L115	89°32'7.654"E to 89°32'12.693"E	27°10'16.533"N to 27°9'52.689"N	757	Major	NNW-SSE	Controlled by drainage *Wangchhu*	Along the Wangchhu river, fall in the reservoir area.
L116	89°31'6.673"E to 89°31'26.48"E	27°11'14.255"N to 27°11'4.864"N	625	Major	Northwest-southeast	Controlled by drainage Wangchhu	Along the Wangchhu river, fall in the reservoir area
L118	89°34'34.494"E to 89°34'52.189"E	27°11'4.197"N to 27°11'6.881"N	500	Minor	ENE-WSW	Controlled by drainage (Tanalum Chhu)	Along Tanalum Chhu, outside of reservoir area.
L119	89°31'15.083"E to 89°31'21.425"E	27°12'28.006"N to 27°12'17.006"N	397	Minor	Northwest-southeast	Controlled by drainage *Wangchhu*	Along the Wangchhu river, within the reservoir area.
L120	89°31'49.75"E to 89°32'7.833"E	27°18'1.57"N to 27°17'51.438"N	580	Major	Northwest-southeast	Controlled by drainage	Righ bank of Wangchhu, outside of reservoir area.
L123	89°33'31.716"E to 89°33'40.395"E	27°17'21.177"N to 27°17'24.408"N	264	Minor	Northeast-southwest	Controlled by drainage	Left bank of Wangchhu, outside of reservoir area.
L124	89°31'9.01"E to 89°31'8.55"E	27°13'10.316"N to 27°12'58.174"N	384	Minor	North-south	Controlled by drainage *Wangchhu*	Along the Wangchhu river, within reservoir area.
L125	89°31'10.256"E to 89°31'13.527"E	27°13'32.198"N to 27°13'49.705"N	552	Major	NNE-SSW	Controlled by drainage *Wangchhu*	Along the Wangchhu river, within reservoir area.
L128	89°34'37.711"E to 89°34'52.954"E	27°18'14.741"N to 27°18'36.758"N	796	Major	Northeast-southwest	Controlled by drainage	L/B of Geynitsang Chhu, outside of reservoir area.

Table 2
Inventory of landslide of Bunakha HEP reservoir area and its vicinity

Slide No.	Area (sq.m.)	Geographic Location/ Coordinates		Type of Slide/ Mode of Failure	Activity	Morphometric Characters / Location	Lithology
		Longitude	Latitude				
1	648.57	89°32'10.562"E	27°8'52.759"N	Rock fall /Toppling	Stable	25m high and 15m wide, just above the MCT-I, right bank of Wangchu, boundary of landslide is within the reservoir, area is thickly vegetated.	Rocks of Paro Formation, rock are dipping towards SSE direction i.e. d/s.
2	316.84	89°31'56.44"E	27°11'4.801"N	Rock cum debris slide	Dormant	20m high and 30m wide, on the right bank of Tanalum Chhu near the confluence with Wangchu, boundary of landslide is within the reservoir, area is moderately vegetated mostly pine trees.	Calcareous unit of Paro Formation, rock are dipping towards SSW direction.
3	708.32	89°31'54.876"E	27°11'3.648"N	Rock slide	Stable	On RB of Tanalum Chhu near the confluence with Wangchhu, boundary of landslide is within the reservoir, area is moderately vegetated mostly pine trees.	Calcareous unit of Paro Formation, dipping towards SSW direction. J1-055/20 (fol.); J2- 010/65 & J3- 065/70.
4	397.97	89°31'46.89"E	27°10'59.696"N	Rock slide (group of slide)	Stable	On the left bank of Wangchhu just u/s of confluence with Tanalum Chhu, boundary of landslide is within the reservoir.	Calcareous unit of Paro Formation
5	553.92	89°31'42.032"E	27°11'1.754"N	Rock slide	Stable	On the left bank of Wangchhu just u/s of confluence with Tanalum Chhu, toe of landslide falls in the reservoir, potential slope instability zone.	Calcareous unit of Paro Formation
6	492.99	89°31'38.245"E	27°11'2.413"N	Rock slide	Stable	On the left bank of Wangchhu just u/s of confluence with Tanalum Chhu, toe of landslide falls in the reservoir, potential slope instability zone.	Calcareous unit of Paro Formation
7	218.48	89°31'20.874"E	27°11'9.888"N	Rock slide	Stable	On the left bank of Wangchhu 533 m u/s from landslide number 6, boundary of landslide is within the reservoir.	Calcareous unit of Paro Formation
8	177.76	89°31'12.475"E	27° 11'13.29" N	Rock fall (Toppling)	Stable	On the left bank of Wangchhu 257 m u/s from landslide number 7, boundary of landslide is	Calcareous unit of Paro Formation

						within the reservoir, area is moderately vegetated.	
9	260.33	89°30'56.639"E	27°11'20.63"N	Rock fall	Stable	20m high and 18m wide, on the left bank of Hachhu 178 m u/s from confluence with Wangchhu, boundary of landslide is within the reservoir.	Calcareous unit of Paro Formation
10	481.26	89°31'1.647"E	27°11'23.191"N	Rock slide	Stable	25m high and 18m width, RB of Wangchhu, 178 m u/s from confluence with Hachhu, landslide is within the reservoir.	Calcareous unit of Paro Formation
11	367.20	89°31'1.073"E	27°11'24.72"N	Rock slide	Stable	18 m high and 20m wide, right bank of Wangchhu,42 m u/s from landslide number 10, landslide is within the reservoir.	Calcareous unit of Paro Formation
12	1103.1 7	89°31'3.099"E	27°11'29.881"N	Rock fall	Stable	22m high and 17m wide, right bank of Wangchhu, 172 m u/s from landslide number 11, boundary of landslide is within the reservoir.	Calcareous unit of Paro Formation
13	222.72	89°31'16.018"E	27°11'46.103"N	Rock slide	Stable	23m high and 19m wide, right bank of Wangchhu, 606 m u/s from landslide number 12, boundary of landslide is within the reservoir.	Calcareous unit of Paro Formation
14	215.19	89°31'15.114"E	27°11'47.331"N	Rock Fall	Stable	Right bank of Wangchhu, 46 m in northwest direction from landslide number 13, boundary of landslide is falling outside the reservoir area.	Calcareous unit of Paro Formation
15	181.32	89°31'14.416"E	27°12'17.741"N	Rock Fall	Stable	Right bank of Wangchhu, 990 m u/s (aerial distance) from landslide number 13, boundary of landslide is falling outside the reservoir area.	Calcareous unit of Paro Formation
16	146.95	89°31'15.97"E	27°12'17.741"N	Rock Fall	Stable	Right bank of Wangchhu, 40 m towards SE direction from landslide number 15, boundary of landslide is within the reservoir.	Calcareous unit of Paro Formation
17	575.31	89°31'11.869"E	27°12'31.357"N	Old rock slide	Stable	22m high and 28m wide, right bank of Wangchhu, 422 m u/s from landslide number 15, boundary of landslide is within the reservoir, area is sparsely vegetated.	Calcareous unit of Paro Formation, rock are dipping towards southwest direction i.e. d/s inside the slope.
18	324.82	89°31'12.196"E	27°12'42.006"N	Rock fall	Stable	22m high and 28m wide,	Calcareous unit of

						right bank of Wangchhu, 324 m u/s from landslide number 17, boundary of landslide is within the reservoir.	Paro Formation
19	231.49	89°31'5.855"E	27°12'57.021"N	Old rock fall	Stable	17m high and 23m wide, right bank of Wangchhu, 482 m u/s from landslide number 18, toe of landslide falls in the reservoir area, area is sparsely vegetated, potential slope instability zone.	Calcareous unit of Paro Formation
20	94.58	89°31'5.759"E	27°13'21.533"N	Rock fall	Stable	Right bank of Wangchhu, 760 m u/s from landslide number 19, boundary of landslide is within the reservoir.	Calcareous unit of Paro Formation
21	256.83	89°31'4.424"E	27°13'22.537"N	Rock fall cum debris slide	Stable	Right bank of Wangchhu, 51 m northwest direction from landslide number 20, boundary of landslide is within the reservoir.	Calcareous unit of Paro Formation
22	228.23	89°31'7.797"E	27°13'26.12"N	Rock fall cum debris slide	Stable	Right bank of Wangchhu, 160 m u/s from landslide number 20, boundary of landslide is within the reservoir.	Calcareous unit of Paro Formation
23	358.06	89°31'8.921"E	27°13'31.601"N	Rock / debris slide	Stable	13m high and 17m wide, right bank of Wangchhu, 177 m u/s from landslide number 22, boundary of landslide is within the reservoir, area is sparsely vegetated.	Calcareous unit of Paro Formation
24	7135.0 8	89°31'32.358"E	27°14'17.703"N	Old rock slide	Stable	35m high and 45m wide, right bank of Wangchhu, just u/s from the confluence with Tham Chhu, toe of landslide is within the reservoir, area is sparsely vegetated, potential slope instability zone.	Calcareous unit of Paro Formation
25	16947. 14	89°31'34.147"E	27°14'30.822"N	Rock fall and debris slide	Active	13m high and 23m wide, right bank of Wangchhu, 375 m u/s from landslide number 24, toe of landslide is within the reservoir, area is sparsely vegetated, potential slope instability zone.	Calcareous unit of Paro Formation
26	562.76	89°31'37.924"E	27°14'59.446"N	Rock/ debris slide	Stable	11 m high and 17 m wide, right bank of Wangchhu, 820 m u/s from landslide no. 25 outside of reservoir	Schist and calc-silicate gneisses, Paro Formation

						area, moderately vegetated with mixed vegetation.	
27	455.61	89°31'38.719"E	27°15'7.596"N	Rock fall and debris slide	Stable	15m high and 23m wide, RB of Wangchhu, 247 m u/s from landslide no. 26, within the reservoir, area is moderately vegetated with mixed vegetation.	Schist and calc-silicate gneisses, Paro Formation
28	348.78	89°31'39.107"E	27°15'8.041"N	Rock fall and debris slide	Dormant	17m high and 24m wide, right bank of Wangchhu, adjacent to the landslide number 27, boundary of landslide is within the reservoir, area is moderately vegetated with mixed vegetation.	Schist and calc-silicate gneisses, Paro Formation.
29	419.25	89°32'23.468"E	27°16'30.731"N	Debris slide	Active	11m high and 15m wide, right bank of Wangchhu near at the confluence with Dudullungpa Chhu, landslide is upstream of the reservoir area, area is sparsely vegetated with mixed vegetation.	Slide scar exposes, fragments of quartz mica schist and metabasic of Paro Formation.
30	615.32	89°32'25.795"E	27°16'32.684"N	Debris slide	Active	12m high and 15m wide, right bank of Wangchhu near at the confluence with Dudullungpa Chhu, landslide is upstream of the reservoir area, area is sparsely vegetated with mixed vegetation.	Slide scar exposes, fragments of quartz mica schist and metabasic of Paro Formation.
31	335.00	89°32'29.494"E	27°17'0.07"N	Debris slide	Dormant	Right bank of Wangchhu, 1 km u/s from the confluence with Dudullungpa Chhu, landslide is upstream of the reservoir area.	Fragments of quartz mica schist and quartzite of Paro Formation.
32	198.32	89°32'48.738" E	27°17'2.308"N	Debris	Dormant	Right bank of Wangchhu, 65 m towards northwest from landslide number 31, landslide is upstream of the reservoir area.	Fragments of quartz mica schist and quartzite of Paro Formation.
33	36472. 17	89°31'1.189"E	27°14'13.365"N	Rock slide	Dormant	In the Paro-Ha road, 864 m towards southwest direction from landslide number 24, landslide is outside of reservoir area.	Calcareous unit of Paro Formation
34	895.28	89°30'51.823"E	27°13'59.467"N	Rock slide	Dormant	In the Paro-Ha road, 500 m towards southwest direction from landslide number 33, landslide is outside of reservoir area.	Calcareous unit of Paro Formation
35	774.69	89°30'48.197"E	27°14'0.726"N	Rock slide	Dormant	In the Paro-Ha road, 98 m towards WWN direction from landslide number 34,	Calcareous unit of Paro Formation

						landslide is outside of reservoir area.	
36	2368.66	89°30'44.975"E	27°13'57.856"N	Rock slide	Dormant	In the Paro-Ha road, 60 m towards southwest direction from landslide number 35, landslide is outside of reservoir area.	Calcareous unit of Paro Formation
37	3119.43	89°30'48.349"E	27°13'57.503"N	Rock slide	Dormant	In the Paro-Ha road, 70 m towards southeast direction from landslide number 36, landslide is outside of reservoir area.	Calcareous unit of Paro Formation
38	84198.29	89°30'44.312"E	27°13'51.168"N	Rock slide	Dormant	In the Paro-Ha road, 150 m towards south direction from landslide number 37, landslide is outside of reservoir area.	Calcareous unit of Paro Formation
39	44047.49	89°30'35.533"E	27°13'54.094"N	Rock slide	Dormant	In the Paro-Ha road, 250 m towards west direction from landslide number 38, landslide is outside of reservoir area.	Calcareous unit of Paro Formation
40	37371.87	89°30'12.367"E	27°13'56.045"N	Rock slide	Dormant	In the Paro-Ha road, 650 m towards west direction from landslide number 39, landslide is outside of reservoir area.	Calcareous unit of Paro Formation
41	39854.66	89°31'54.089"E	27°11'19.052"N	Old rock fall	Dormant	135m high and 253m wide, at Phutsholingh-Thimphu road near Chapcha, landslide is outside of reservoir area, area is moderately vegetated mostly pine trees.	Calcareous unit of Paro Formation, four joints are prominent: J1-330(dip direction)/10 (dip amount) (foliation); J2-030/70; J3-165/65 & J4 – 080/46 (valley dipping)
42	137229.03	89°32'10.874"E	27°11'15.894"N	Old rock slide	Dormant	189m high and 258m wide, at Phutsholingh-Thimphu road near Chapcha and 500 m from landslide 41 towards eastern direction, landslide is outside of reservoir area, area is moderately vegetated mostly pine trees.	Calcareous unit of Paro Formation, four joints are prominent: J1-330/10 (foliation); J2- 030/70; J3-165/65 & J4 – 080/46 (valley dipping).
43	480.58	89°30'29.789"E	27°11'31.363"N	Rock slide	Dormant	Left bank of Hachhu, 950 m u/s from confluence with Wangchhu, boundary of landslide is within the reservoir.	Calcareous unit of Paro Formation
44	402.39	89°30'31.206"E	27°11'30.3"N	Rock	Dormant	Left bank of Hachhu, 900	Calcareous unit of

				slide		m u/s from confluence with Wangchhu, boundary of landslide is within the reservoir.	Paro Formation
45	263.13	89°30'33.037"E	27°11'29.03"N	Rock slide	Dormant	Left bank of Hachhu, 870 m u/s from confluence with Wangchhu, boundary of landslide is within the reservoir.	Calcareous unit of Paro Formation
46	162.56	89°31'12.352"E	27°13'47.295"N	Rock slide	Dormant	Left bank of Hachhu, 840 m u/s from confluence with Wangchhu, boundary of landslide is within the reservoir.	Calcareous unit of Paro Formation
47	220.95	89°31'12.855"E	27°13'48.762"N	Rock slide	Dormant	Left bank of Hachhu, 780 m u/s from confluence with Wangchhu, boundary of landslide is within the reservoir.	Calcareous unit of Paro Formation
48	162.56	89°31'12.352"E	27°13'47.295"N	Debris slide	Active	Right bank of Wangchhu, 500 m u/s from landslide number 23, boundary of landslide is within the reservoir, area is moderately vegetated with mixed vegetation.	Slide scar exposes, fragments of marble and metabasics of Paro Formation
49	220.95	89°31'12.855"E	27°13'48.762"N	Debris slide	Active	Right bank of Wangchhu, 60 m u/s from landslide number 48, boundary of landslide is within the reservoir, area is sparsely vegetated with mixed vegetation, potential slope instability zone.	Slide scar exposes, fragments of marble and metabasics of Paro Formation
50	1410.0	89°32'31.466"E	27°08'4.301"N	Debris slide	Active	Right bank of Wangchhu, 300 m u/s from the dam axis, area is densely vegetated, landslide would be partially submerged.	Slide scar exposes, fragments of banded gneisses and foliated gneisses of Thimphu Formation
51	18764.2	89°32'22.973"E	27°08'52.952"N	Debris slide	Active	30 m high and 300m wide, along bypass road, due to road cutting, u/s of dam axis on the left bank of Wangchhu, boundary of landslide is outside of reservoir area.	Slide scar exposes, fragments of calc silicate gneisses, banded gneisses and marble of Paro Formation

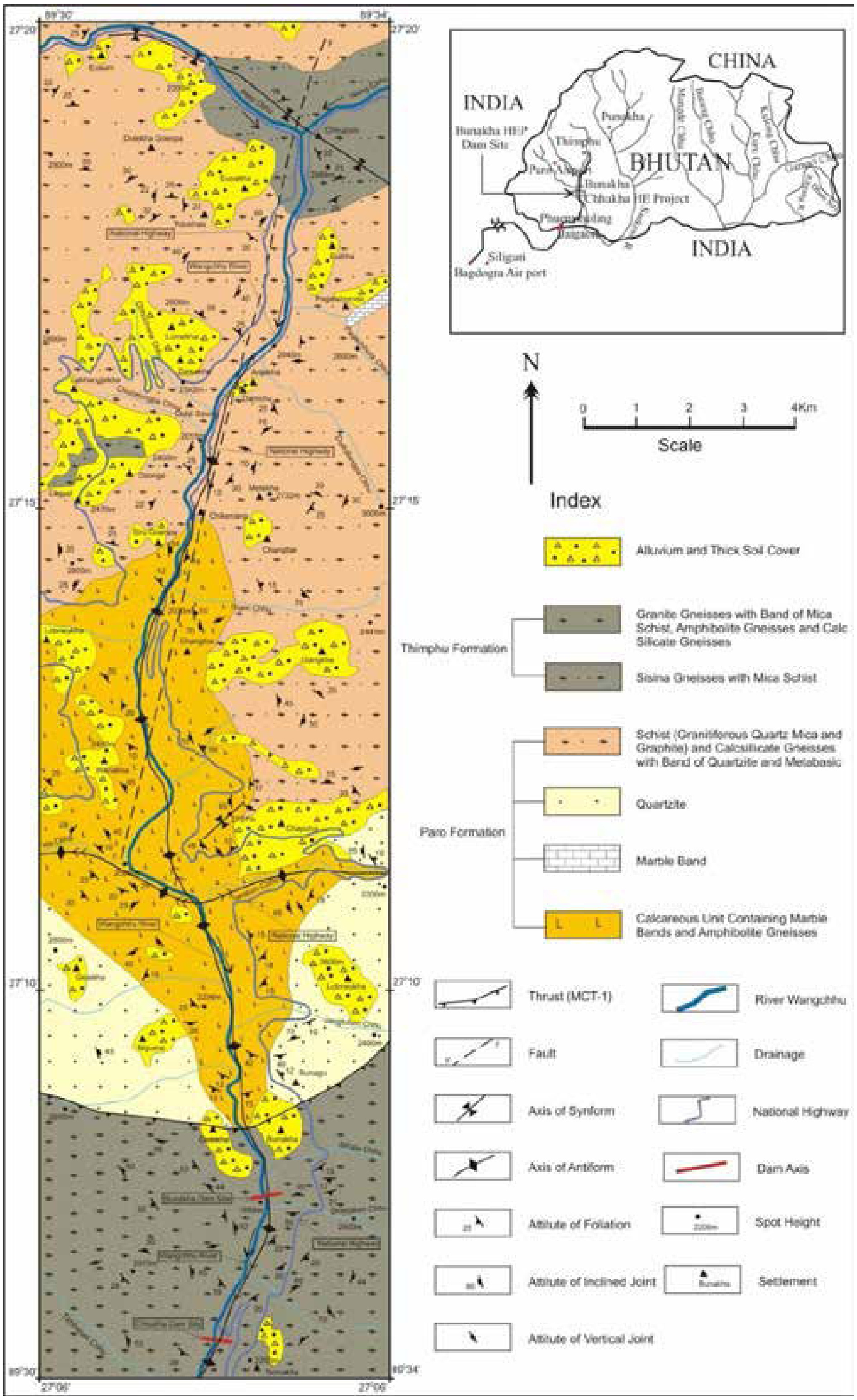

Figure 1 Geological map of the Bunakha dam reservoir area (after Geological and Mineral Map of Bhutan by Geological Survey of India, 1979-80, Mishra and Sanwal, 1994, Koike, 2001, 2002 and Author's Field Traverses).

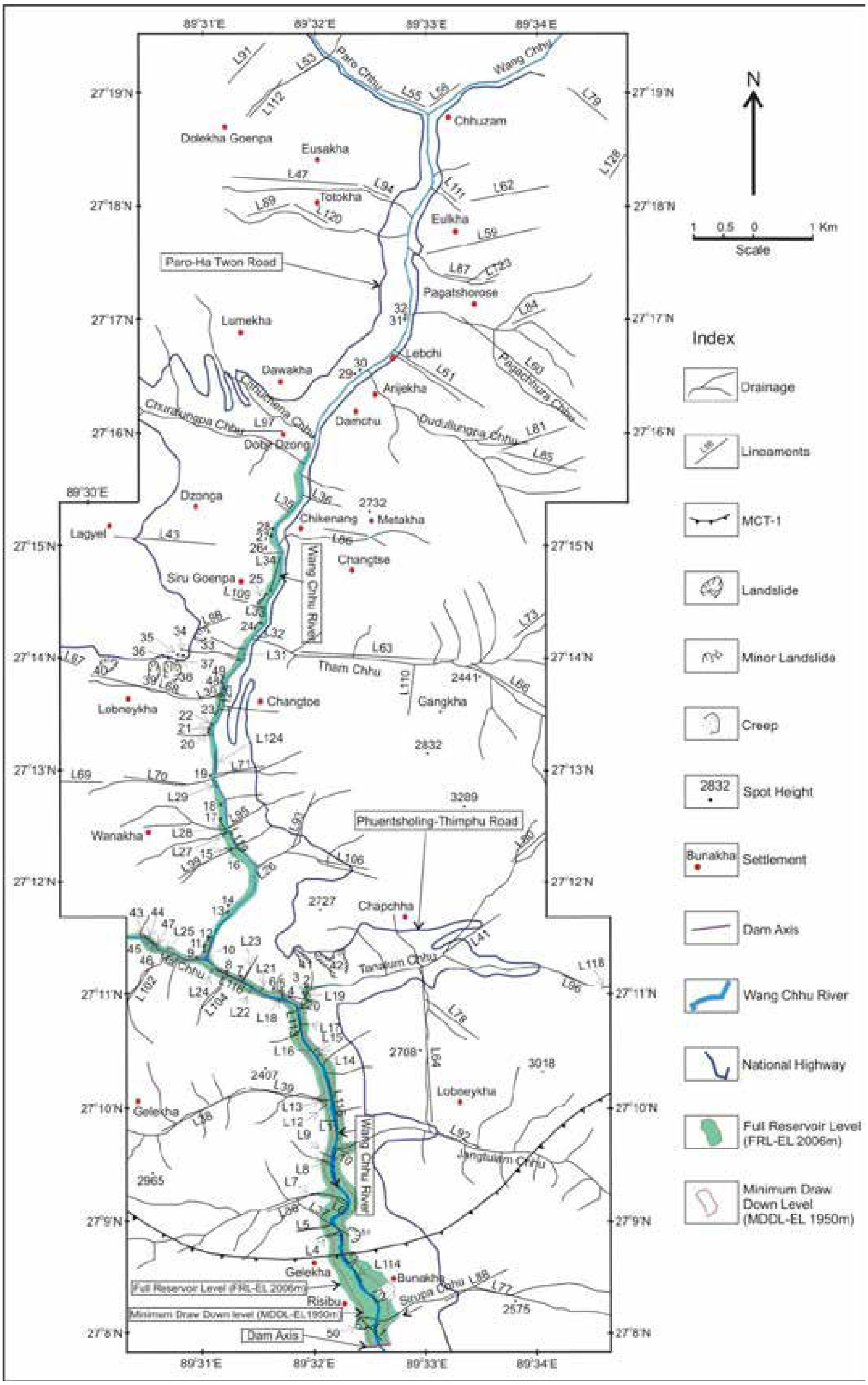

Figure 2 Landslide location, lineament and drainage map of the Bunakha hydroelectric project reservoir area.

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