is assumed to be constant in both cases, the peak discharge (PMF) at the powerhouse site is estimated to be 9,400 m^3/s.

(3) Design Discharge for Diversion: 490 m^3/s

As the critical path of this project is not on the construction of dam, the period of dam construction can be limited to dry season only (from November to April). Accordingly, the diameter of diversion tunnel and the height of cofferdam can be reduced, giving favorable impact on the project economy. Tables 5-9 and 5-10 indicate the results of frequency analyses and the value of 490 m^3/s is found at the nodal point of November and 10-year return period in Table 5-10.

5.7 Glacier Lake Outburst Flood (GLOF)

5.7.1 General

The occurrence of glacier lake outburst flood (GLOF) is often reported in the areas such as the Himalayas, Alaska, European Alps, Northern Europe, Andes, etc. where rivers have their origins in glacial ranges. According to recent studies, it becomes clear that occurrence of GLOF is not a very rare event in the above-stated areas.

In Nepal, the big floods by GLOF caused heavy damages on the river structures in recent years 1981 and 1985. In view of the above, the effects of GLOF on the structures planned on the river having glaciers at its origin like this project have to be carefully taken into consideration, in addition to those of common flood caused by rainfall.

This chapter first describes the records of past GLOF and mechanism of GLOF occurrence, then, the result of simulation analysis with computer (FACOM 380S) of surge wave propagation upto the dam site of prescribed flood originated at a glacier lake selected based on the study of glacier lake distribution at the upper reach of the Arun river referring to the available documents as well as the LANDSAT images. Lastly, the countermeasures against GLOF and recommended warning system is described to ensure the safety of the project structures.

It is noted that the information contained in the Interim Report (Preliminary Study of the Glacier Lake Outburst Flood (GLOF) Phenomenon in the Nepal Himalaya (Phase 1 - Interim Report by WECS, 1986)) released by the Water and Energy Commission of HMG/N has been extensively utilized for this study and the valuable advices on the Himalayan glaciers are also given by Prof. K. Higuchi, Associate Prof. Y. Ageta, Water Research Institute of Nagoya University, Japan and H. Fushimi, Lake Biwa Research Institute.

5.7.2 Past Records

(1) Records in Nepal

Table 5-11 and Fig. 5-13 show records of GLOFs in Nepal which include cases having origins in the Tibetan area. Brief explanation of each record is given below in chronological order. The number of each sentence corresponds to the figure in Table 5-11 and Fig. 5-13.

1 Pokhara (approx. 600 years ago)

According to Carson (Erosion and Sedimentation Processes in Nepalese Himalaya, ICIMOD, 1985), it is estimated that the glacier lake of about 10 km^2 in area size located back of the Mt. Machhapuchare was burst about 600 years ago and the Pokhala valley was covered with tremendous amount of earth and sand (average 50 to 60 m in thickness).

2 Arun river (around 1964)

According to inhabitants in the Arun river basin, it is reported that the remains of timber, concrete, truck bodies, etc., presumablly from Tibet, were flushed together with enormous volume of debris around 1964 (another predates a little).

Table 5–11 List of GLOFs in Nepal

No.	Date	Location	Available Information of Data
①	Approximately 600 years ago	Pokhara Valley	Not Available
②	1964?	Arun River	Not Available
③	1964	Bhote Kosi	Glacier Lake : Zhangzangbo Glacier Scale is relatively small.
④	Sep.3,1977	Dudh Kosi, Mingbo Valley	Glacier Lake : Nare Glacier, 4,000,000㎡ Peak Discharge : 1,300㎡/s(at Rabuwa Bazar)
⑤	Jul.24~25,1980	Tamur River	Not Available
⑥	Jul.11,1981	Bhote Kosi (Boqu River)	Glacier Lake : Zhangzangbo Glacier, 19,000,000㎡ Peak Discharge : 15,920㎡/s
⑦	Aug.4,1985	Bhote Kosi, Langmoche Valley	Glacier Lake : Langmoche(Dig Cho)Glacier, 6,000,000~10,000,000㎡ Peak Discharge : 2,000㎡/s at least

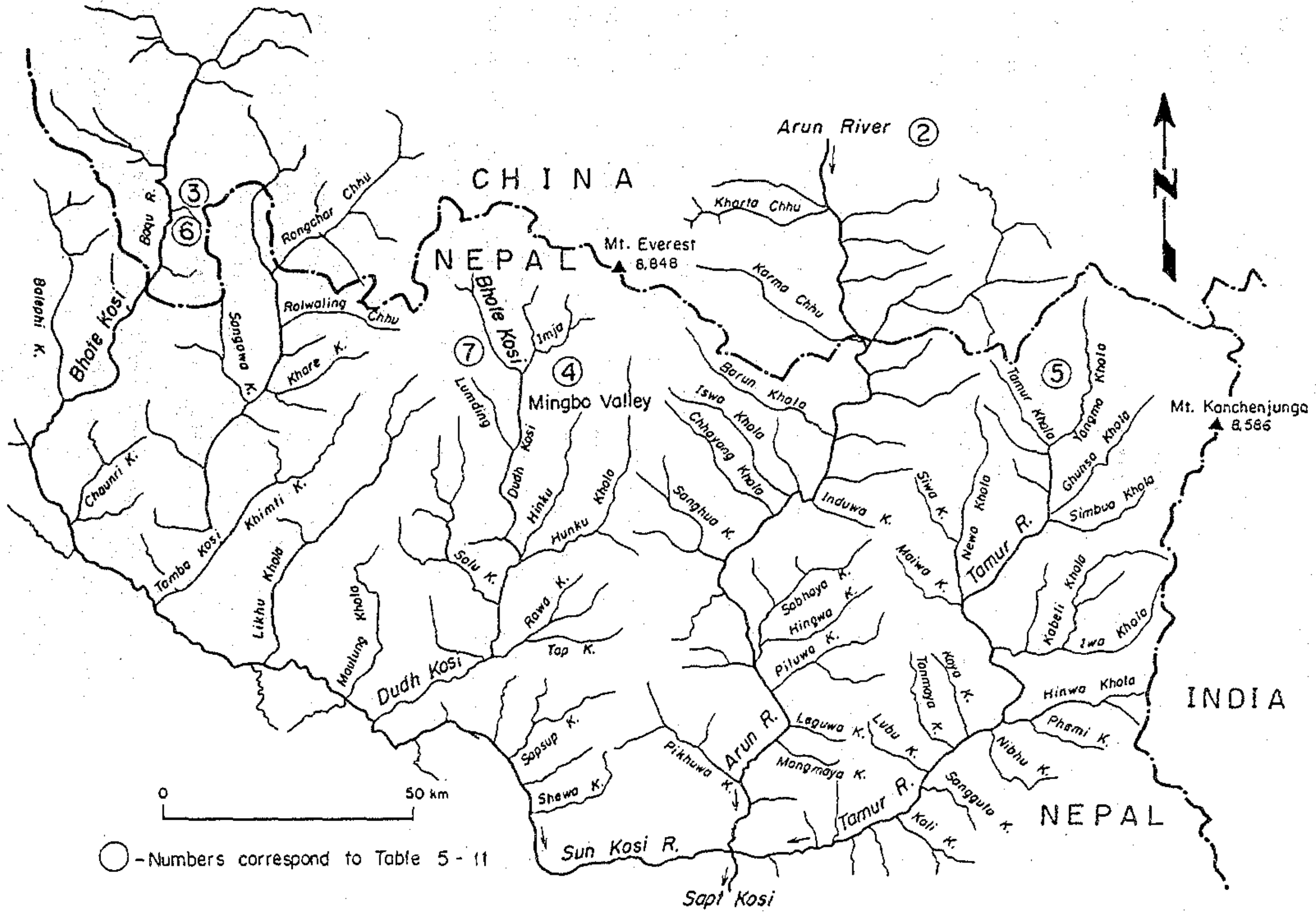


Fig. 5–13 Location Map of GLOF in Nepal

3 , 6 Bhote Kosi (1964 and 1981)

The Bhote Kosi river is the upper reach of the Sun Kosi river and is called as the Boqu river in China. In this area, large flood twice occurred at the end of the Zhangzangbo glacier and subsequently confirmed as GLOF in 1964 and 1981. Though the 1964 GLOF is of rather small scale, the peak discharge of that in 1981 is estimated at 15,920 m^3/s which cut the Nepal-China Highway connecting Nepal and China at many points and also damaged the sluice-way gate of the Sun Kosi power station [refer to Characteristics of Debris Flow Caused by Outburst of Glacial Lake in Boqu River in Xizang, China, 1981, by Xu Daoming, 1985].

4 Dudh Kosi, Mingbo Valley (Sept. 3, 1977)

The Dudh Kosi is a tributary of the Sun Kosi river and originates in the Khumbu area near Mt. Everest. The size of glacier lake (at the end of Nare glacier) is presumed to be $4 \times 10^6 m^3$ to $5 \times 10^6 m^3$ in volume and the hydrograph of this GLOF was measured at Rabuwa Bazar in the downstream area [refer to 1) IAHS Publ. No. 149, Nepal Case Study: Catastrophic Floods, H. Fushimi et al, 1985 and 2) Mountain Hazards Mapping in the Khumbu Himal, Nepal, with Prototype Map, Scale 1:50,000, M. Zimmermann et al in Mountain Research and Development, Vol. 6, No.1, 1986].

5 Tamur river (July 24 to 25, 1980)

GLOF occurred at the Tamur river though the details such as the origin, size, etc. are not known. It is reported that all trees upto 20 m high above the river bed were flushed over a 30 km stretch along the river.

7 Bhote Kosi, Langmoche valley (August 4, 1985)
(This river is different from case 3 , 6 though the same name.)

Similarly to the case of 4 above, GLOF occurred at the Langmoche glacier in the Khumbu area and its size is presumed to be 6 x $10^6 m^3$ to 10 x $10^6 m^3$ in total volume and peak discharge of around 2,000 m^3/s. In this case, all facilities of the Namche Small Hydel Project nearing completion were wholly destroyed [refer to Glacier Lake Outburst Flood (Jökulhlaup) on the Bhote/Dudh Kosi - August 4, 1985, by V.J. Galay, 1985].

(2) Records in Other Countries

As previously stated, occurrences of GLOF phenomena have been reported in various parts of the world, however, it is considered that since the meteorological conditions, type of GLOF, etc. in the countries far apart from Nepal are distinctly different from those in Nepal, only the reports from the neighboring countries are described (refer to Fig. 5-14).

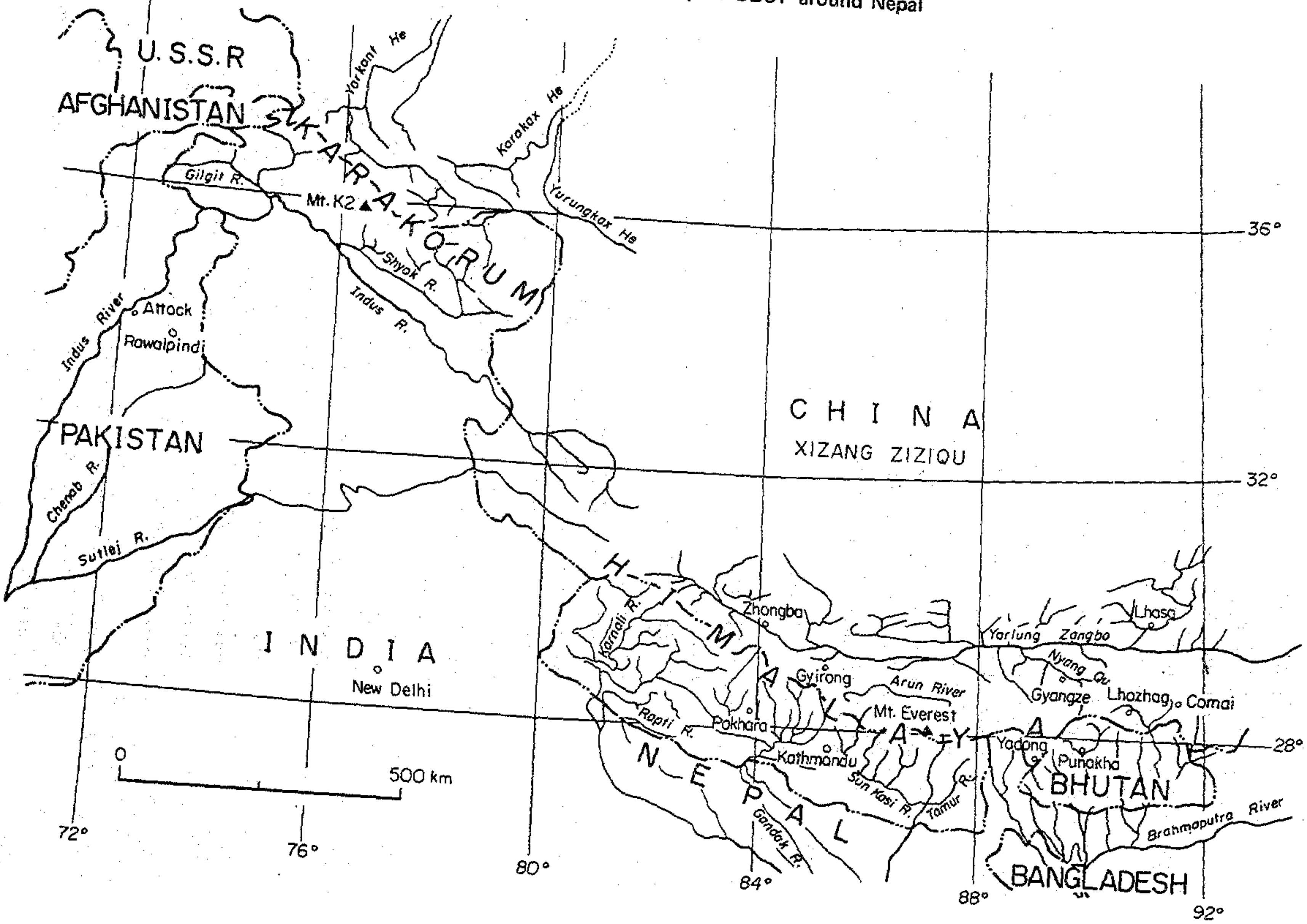
(i) Pakistan (Hewitt, 1985, IAHS No. 149)

In Pakistan, 35 cases of GLOF are recorded in the past 200 years and there are many GLOF prone areas at various parts of the country. Glaciers in Pakistan are broadly classified into two; the one as those at the Karakorum range and the other at the Hindu Kush range, while, the rivers are divided into the Indus and Yarkant rivers running south and north of the above mountain ranges, respectively. Glaciers in these areas are characterized by their large length compared with those at the Nepal Himalaya and accordingly, the nature of glacier lakes is also quite different.

Glacier lakes in Nepal are generally formed by moraine dams (deposit formed at the end of glacier) or moraine dams with ice cores, while in Pakistan, the closure of neighboring river by glacier, namely the ice dam, is frequently observed. In the case of glacier lakes by ice dam, GLOF tends to frequently occur because of inherent repetitive nature of failure and subsequent reformation of ice dam.

The Shyok river being the upper reach of the Indus river has suffered from repeated large floods in the past and this mainly owes to the failure of glacier lake created on

Fig. 5–14 Reference Map of GLOF around Nepal



the Shyok river by the Chong Khumdan and Kichik Khumdan glaciers located at the upper tributaries of the Shyok river. Among others, a tremendous GLOF occurred on August 15, 1929, the details of which are indicated below.

Gracier Lake (1929)		Observation at Attock, 1194 km downstream of the glacier dam	
Length of lake	: 16 km	Max. flood rise	: 8.1 m
Average width	: 1.6 km	Rise to peak	: 17 hrs
Depth of dam	: 120 m	Duration of wave	: 70 hrs
Volume	: $1.5 \times 10^9 m^3$	Traveling time from dam	: 81 hrs

Further, GLOFs at the Yarkant river (China) running north of the Karakorum range are also reported, 9 times during the period from 1959 to 1984. GLOF occurred every year during the limited years after 1978 except 1981. The magnitude of the peak discharge of these GLOFs is estimated at a range of 800 m^3/s to 6,270 m^3/s and based on this assumption, volume of glacier lake is considered to be around 10^6 to $10^7 m^3$.

(ii) Bhutan (Gansser, 1970, The Mountain World)

In the Himalayan area north of Bhutan, there exist many glacier lakes and also traces of glacier lakes once created. The flood ever attacked Punakha is presumed to be caused by failure of glacier lake in the Lunana area at the upstream reach of the Sankosh river. The size of glacier lake estimated from historical traces is found to be as big as $10^7 m^3$ and there is a fear of GLOF occurrence in the future. Glacier lakes in this area are of moraine dams similar to those in Nepal.

(iii) Tibet (Rivers and Lakes of Xizang, 1984)

There exist many glacier lakes in Tibet and lake surface area varies in wide range from 1 km2 to some 10 km2. Two GLOFs are introduced in the above report.

a) July 16, 1954 at upper reach of the Nyang Qu river being a tributary of Yarlung Zangbo river

The glacier lake is of approx. 250 x $10^6 m^3$ in volume and the peak discharge of 7,000 m^3/s to 10,000 m^3/s was recorded at Gyangze in the downstream area.

b) July 10, 1940 at Yadong near the Bhutan border

The glacier lake is of approx. 5 x $10^6 m^3$ in volume and the rise of river surface of 4 m to 5 m was observed. The peak discharge is presumed to be around 3,700 m^3/s.

Other than the above, 9 GLOFs have been confirmed after 1940 at the places; Lomai, Lhozhag, Gyirong and Zhongba located north of the Himalayan range.

5.7.3 Mechanism of GLOF Occurrence

(1) Process of Forming Glacier Lake

Glacier lake is generally classified into the following 3 categories according to the materials forming the dam.

(i) Moraine dammed lake

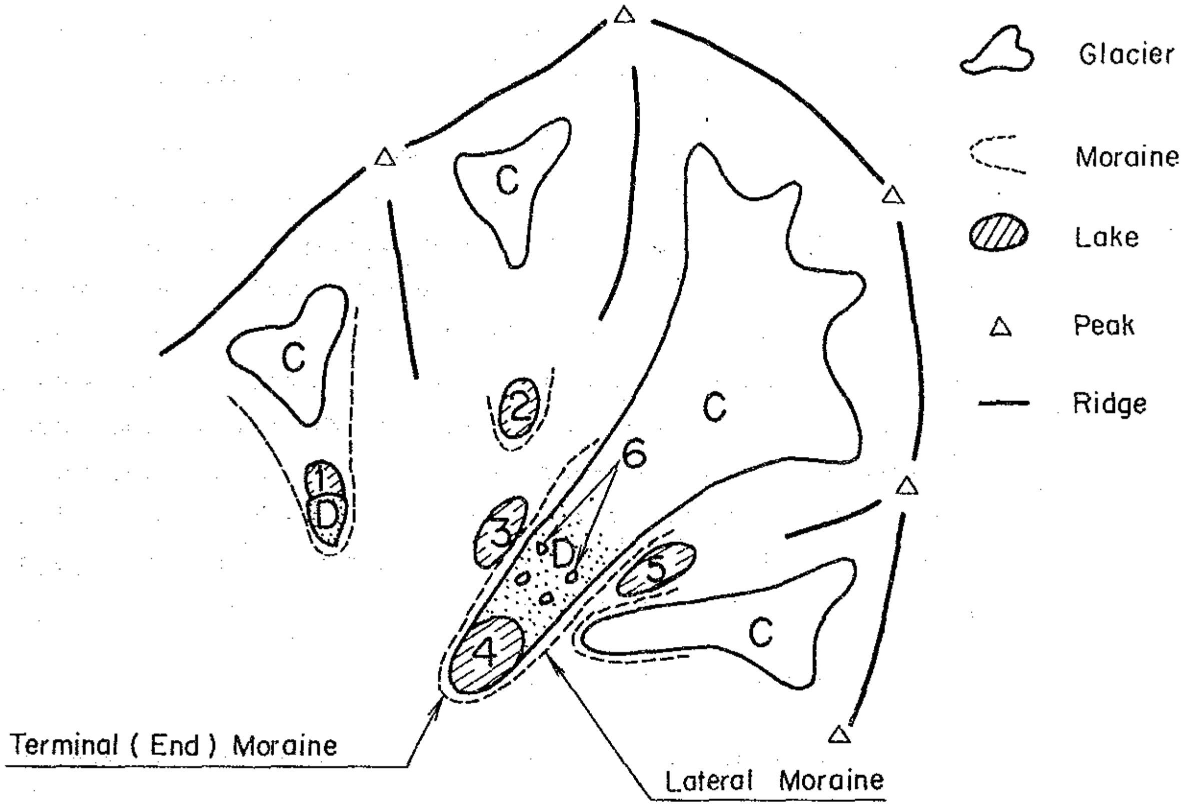
(ii) Glacier ice dammed lake

(iii) Ice-core moraine dammed lake

Other than the above classification, glacier lakes can be further subdivided according to dam type, location, size, etc. as shown in Fig. 5-15.

In the Nepal Himalayan area, many glacier lakes which are dammed by moraine or moraine with ice-core are widely distributed making the source of GLOF. The process of creating glacier lake of this kind is presumed to take the following steps (The Mountain World, Gansser, 1970); (1) advancement of large glacier (as late as 18th to 19th centuries) and formation of a large sized moraine deposit at its end, (2) recession of

Fig. 5–15 Glacier Lake Classification (by H. Fushimi)



Definition of Glacier (by S. Moribayashi)

C Type : Clean type is not almost covered with debris

D Type : Dirty type is covered with debris

① Glacier Lake between C and D

② Moraine Dammed Lake

③ Lake Dammed in Tributary

④ Proglacial Moraine Dammed Lake

⑤ Interglacial Lake

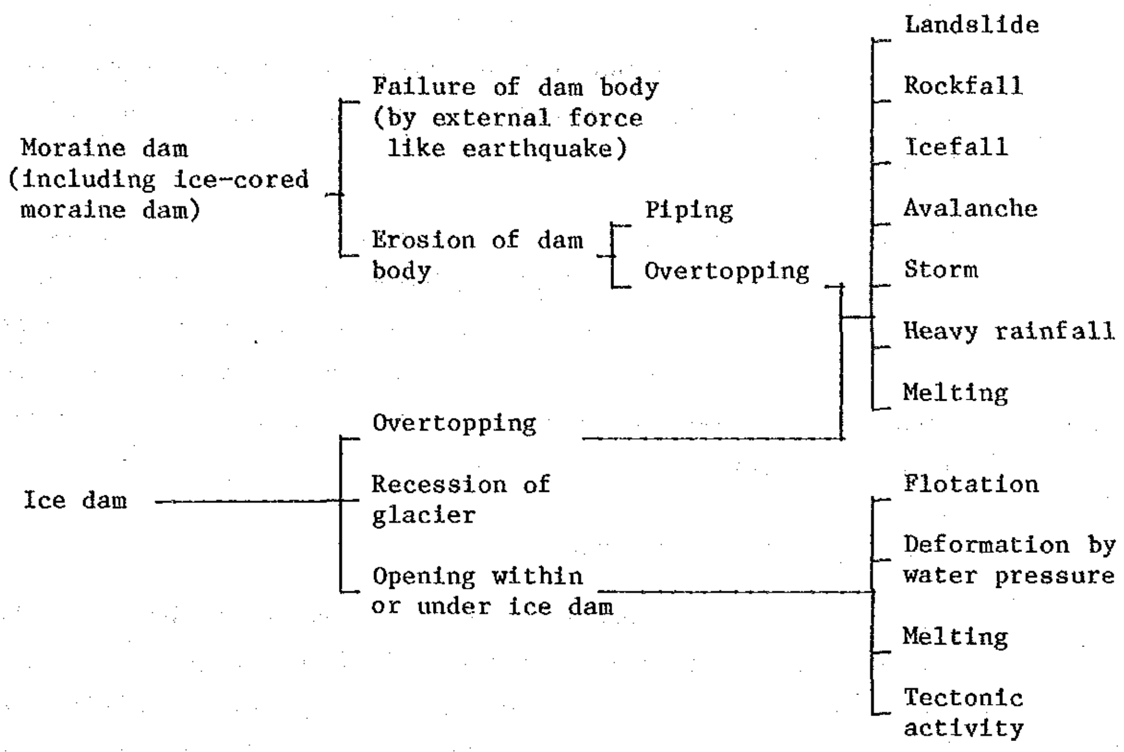
⑥ Ablation Lake

glacier due to certain reasons (mostly climatic conditions) and (3) formation of glacier lake by damming water inside the moraine. A big moraine has a height of more than 100 m and volume of glacier lake formed by dam of this size will become as large as $10^6 m^3$ or even upto $10^7 m^3$ sometimes. Moraines are divided into ice-cored moraine type or simple moraine type, depending on inclusion of remains of ice body therein.

In the Himalayan area, there exist many glaciers covered with rock fragments which shade solar radiation and the remains of glacier so called "dead ice" are outliving in moraine for a long time even after recession of glacier. While, the phenomena of forming glacier lakes due to river closure by glacier itself are observed quite often at many places in the world such as Alaska, European Alps, etc. In the case of the surge of glacier (abrupt forward movement of glacier presumably caused by earthquake, heavy snowfall in short time, avalanche, ice-fall, sudden change of temperature, etc.), there is a high possibility of desastrous damages caused therefrom.

(2) Causes of Failure of Glacier Lake

The causes of failure of glacier lake can be categorized as shown below:



Among the factors indicated above, it is considered that the piping in moraine dam including ice-cored one and the overtopping due to icefall at the end of glacier are the prevailing factors for triggering GLOFs observed in the Himalayan area. Causes for piping depend upon quality and thickness of moraine, and further, temperature in the case of ice-cored moraine. Since the failures of glacier lakes are frequently observed during the monsoon season from July to September, the following serial processes of dam failure will be presumed conveniently.

With increase of inflow to the glacier lake due to melting of glacier by rainfall and/or high temperature, the surface of glacier lake will rise up resulting in eventual overtopping or increase of seepage water through moraine. In the case of ice-cored moraine, high temperature may cause the loosening of ice-core and its ambient frozen soils and accelerate seepage of water.

Under the above-stated conditions that the lake surface is kept at high elevation due to continuous supply of water from the upstream and loosening of moraine dam body is considerably progressed and further, if overtopping of considerable amount of water takes place due to heavy rainfall, icefall, etc., then the moraine dam will dash toward erosion failure as can readily be imagined.

Failure of an ice dam may follow almost the same process as that of moraine dam in principle, however, there are still some differences that the failure of ice dam is processed rather slowly compared with that of moraine dam and that it will be repeated any number of times at the same place due to new movement of glacier.

(3) Propagation of Flood Surge

Different from the case of ordinary flood caused by rainfall, the hydrograph of GLOF is characterized by sharp rise to and fall from its peak. However, there is a certain difference between the shapes of hydrographs for cases of moraine dam and ice dam. Hydrograph due to failure of moraine dam shows more pointed peak than that of ice dam. This mainly owes to the different time of failure, namely, the failure of moraine dam progresses within the range of time from some 10 minutes to several hours, while in the case of ice dam, flood discharge increases gradually and reaches its peak within the range of several days. This difference of failure mechanism indicates that the peak flood discharge caused by failure of moraine dam tends to be bigger than that of ice dam, even if both glacier lakes have the same storage capacity.

The propagation of flood toward downstream basin is greatly governed by configuration of riverbed portion. As observed in the past records, peak discharge attenuates as it goes downstream. But this can't be said unconditionally because of complexity of GLOF propagation characterized by continuous river scoring and deposition of debris and subsequent flood detention and release. For example, the attenuation of peak discharge from 15,000 m^3/s to 2,000 m^3/s in 50 km was observed in GLOF occurred at the Bhote Kosi river in 1981.

As GLOF generally contains a lot of debris, there is a possibility of closure of the other river by debris at its junction and in the case of additional failure of such debris dam, the propagation process will differ from simple one stated above. In any case, GLOF has effect on the basin far downstream as recorded in Pakistan (see 5.7.2), in which river surface rose 8.1 m at the point 1,200 km downstream from the site of GLOF occurrence.

(4) Debris Transport

The amount of debris transported by GLOF is a very important factor in the designs of dam and appurtenant structures. Materials of debris include firstly the flushed moraine itself and then the huge amount of debris scored at river bed as well as both river banks by GLOF. However, it is difficult to quantify the debris contained in GLOF, further, it is impossible to measure the actual values at this stage because no measuring facilities are established.

There is a record showing average density of 50,000 mg/l immediately downstream of glacier lake, as referred to the measurement record of GLOF occurred at the Nostetuko river in Canada (Blown and Church, 1986). The actual density is considered to be several times as large as the above value and may be in the range of 200 x 10^3 mg/l to 300 x 10^3 mg/l.

In addition to the amount of debris to be transported, the maximum size of debris is also the important factor to be considered in the designs of gate, trashrack, etc. According to field observation, it is confirmed that big rock as large as house was flowing down.

It may be easily understood that the amount of suspended loads contained in river discharge will be greatly changed after GLOF. Practically, the periodical measurement at Mulghat on the Tamur river from June 1978 to January 1981 indicated that the amount of suspended load after GLOF of July 1980 is almost four times that measured before. It is further presumed that the suspended load contained in that GLOF would be 50,000 mg/l to 200,000 mg/l (Electrowatt, 1982).

5.7.4 Distribution of Glacier Lake in Arun River Basin

In order to prevent the Arun 3 dam from damages caused by GLOF in the future, the preliminary studies concerning locations and their approximate sizes of glacier lakes distributed in the Arun river basin including China are made, referring to the following data.

Map	1/1,000,000	OPERATIONAL NAVIGATION CHART ONC H-9 BY DMAAC (Defence Mapping Agency Aerospace Center), 1978
	1/500,000	Nepal by Apa Productions
	1/250,000	ATLAS OF THE WORLD BY THE TIMES
	1/192,500	LATEST TREKKING MAP DHANKUTA TO KANCHENJUNGA, MT. EVEREST, MAKALU & ARUN RIVER, 1985/86
	1/50,000	MT. MAKALU, APSUWA KHOLA, KIMASANGKA and TIPTALA BHANJYANG by Topographical Survey Branch Department of Surveys HMG/Nepal, 1982

LANDSAT Imagery

LANDSAT No.	Date	Band	Scale
139-40	May 20, 1984	7	1/1,000,000
139-41	Mar. 17, 1984	7	1/1,000,000
140-40	May 19, 1984	7	1/1,000,000 1/200,000
140-41	Apr. 9, 1984	7	1/1,000,000 1/200,000

Out of the above data, 1/1,000,000 and 1/500,000 scale maps are mainly used for estimating the configurations of tributaries in the

Tibet area. As 1/192,500 and 1/50,000 scale maps are only available for the area in Nepal, they are used for finding the details of the Barun Khola which takes its rise at Mt. Makalu. In these maps, a noticeable glacier lake (Barun Pokhari) is found at the end of the Barun glacier and the failure of this glacier lake is applied to the simulated calculation in the succeeding paragraph. Further, according to these maps, no significant glaciers affiliated with lakes are found in Nepal, other than the Barun Khola.

After observations with the above maps, all identified glaciers that may have lakes were counterchecked in detail by LANDSAT images and the possible existence of glacier lakes are finally made out as shown below and in Fig. 5-16.

Since no field investigation nor aerophotographic survey is conducted in this study, the possibility of existence of glacier lakes is only indicated without confirmation at the site, and therefore, it is desirable to carry out the site investigation with cooperation of China in the Tibetan area. Realistic analyses on GLOF phenomena will then be possible using detailed and reliable information.

1 Barun Pokhari : Lake area approx. 0.3 km^2

2 Barun Khola (left bank) : Lake area approx. 0.3 km^2

3 Iswa Khola : Lake area approx. 0.1 km^2

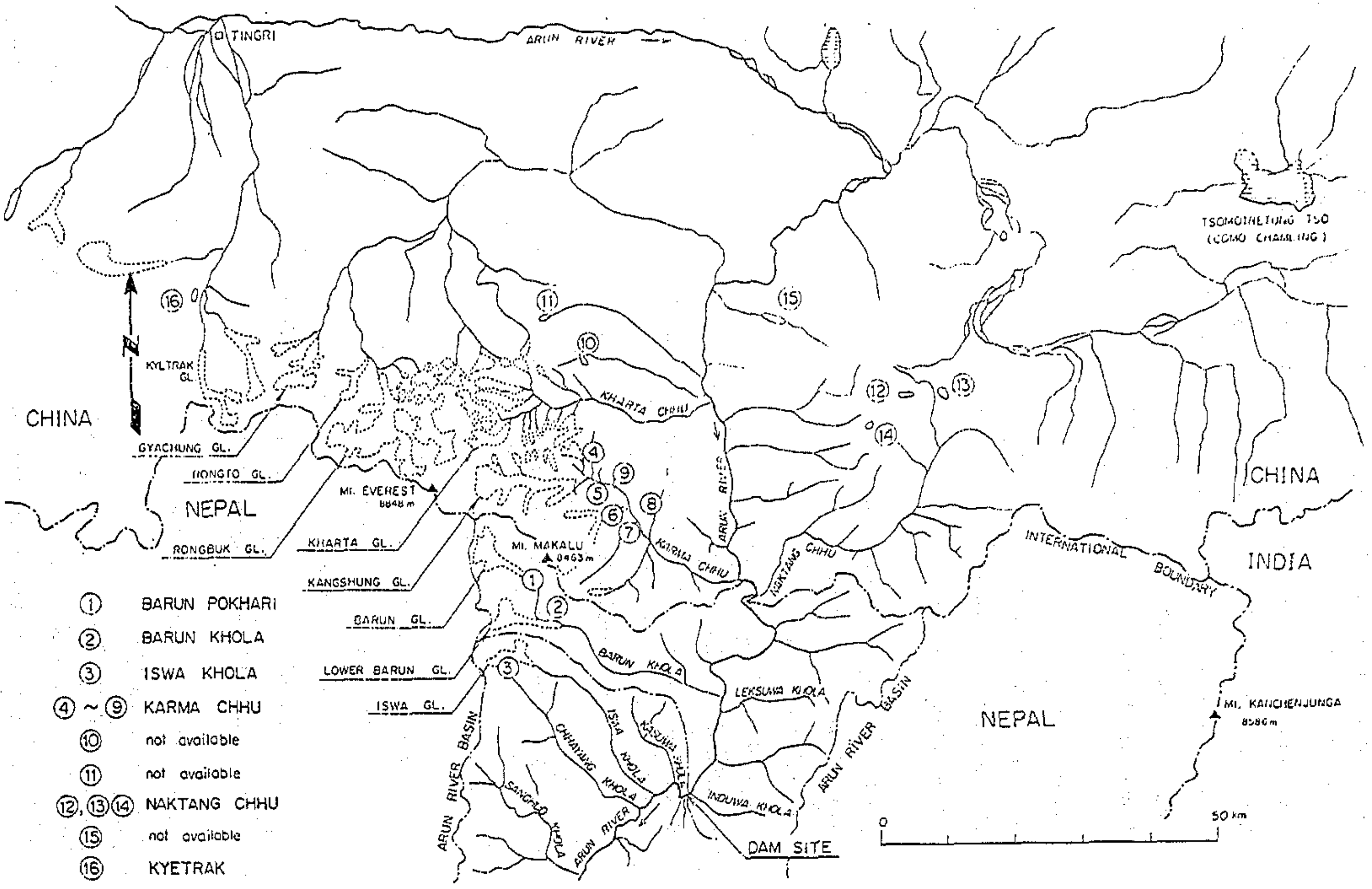
4 - 9 Karma Chhu Basin :

On both banks and tributaries, there are 10 locations where glacier lakes with surface area of 0.1 km^2 to 0.3 km^2 may exist. But LANDSAT images could not prove that all of them are actually glacier lakes.

10 & 11 Tributaries on right bank of the Arun river near the Kharta Chhu :

Both lakes are of large sizes with surface area of appro. 0.7 km^2, however, there is a possibility that they are natural lakes instead of glacier lakes in consideration of their locations.

Fig. 5–16 Location Map of Glacier Lakes in Arun River Basin



12, 13 & 14 Naktang Chhu Basin :

Lake areas are approx. 1.0 km^2 as to 12, 13 and approx. 0.5 km^2 as to 14. These lakes cannot be also decided as glacier lakes by LANDSAT images only.

15 Tributary on left bank of the Arun river:
Lake area approx. 1.0 km^2

16 Around Kyetrak : Lake area approx. 1.0 km^2

5.7.5 Analysis of GLOF

(1) Adopted Model

Since the information and data sufficient for undertaking analysis of GLOF are not available, it is difficult to realistically presume the frequency, magnitude, etc. of future GLOF for this project. Hence, in order to find a clue to countermeasures against GLOF, propagation and peak discharges of a prescribed GLOF at various downstream spots including dam site are analyzed by computer simulation based on quite limited information.

The adopted computer program (EPDC UNSTEADY FLOW ANALYSIS MODEL) is to analyze the unsteady flow using the differential integration method and its specific advantages are as follows:

- Acceptance of intermediate inflow at junction with tributaries
- Boundary conditions of flow and water level can be given irrespective of time at upstream and downstream ends of river as well as at intermediate inflow points
- River cross-sections with arbitrary shape can be input.
- Various losses due to changes of cross-sections and friction coefficient, bend, etc. can be specified.

While, it has the following restrictions:

- Applicability to simulating super-critical flow is limited.

° No count of effect of debris flow

In performing the model analysis like this case, it is indispensable to verify the results with the actual measurement. However, there are no measurement records in the Arun river basin which can be utilized to calibrate the analytical model to produce realistic results. Present study adopts various input conditions indicated in the GLOF report prepared by WECS, in which attempts were made for such calibration.

(2) Input Conditions

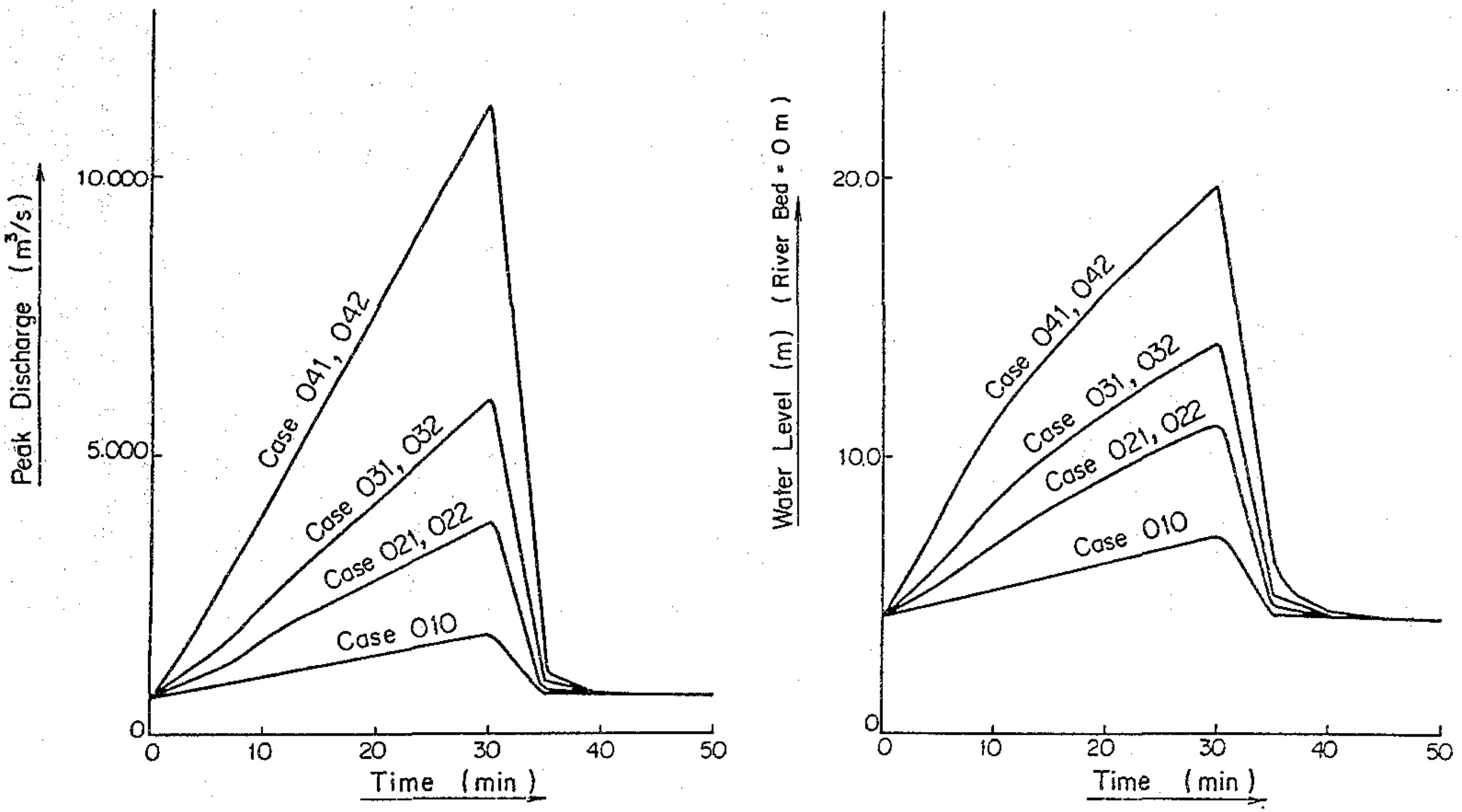
(i) Location of GLOF occurrence

Among the known lakes on the maps as stated in 5.7.4, the location of a GLOF prone lake is fixed at the glacier lake existing at the end of glacier in the upstreammost reach of the Barun Khola considering a key factor that the lake is situated at the nearest distance from the dam site. However, because of the application difficulty of the program under super-critical flow condition, the present simulation model excludes the calculation of the surge phenomenon along the Barun Khola having the average gradient of 1:11 which is steeper than the critical slope. Hence, the actual input condition for discharge is set out at the junction of the Barun Khola with the Arun river proper.

(ii) Glacier lake size

According to interpretation of the 1/50,000 scale map as well as LANDSAT imagery enlarged to 1/200,000 scale, the glacier lake at the Barun Khola will have its area of approximately 0.3 km^2. Assuming its depth of some 10 m, the lake volume will be in the range of $1 \times 10^6 m^3$ to $5 \times 10^6 m^3$. Four cases of lake volume: $1 \times 10^6 m^3$, $3 \times 10^6 m^3$, $5 \times 10^6 m^3$ and $1 \times 10^7 m^3$, are selected for calculation and it is also assumed that the failure of dam will be finished in 30 minutes for every cases as indicated in Fig. 5-17.

Fig. 5–17 Peak Discharge and Water Level at Junction of Arun River and Barun Khola during GLOF



For conservative reasons, the input discharge condition is assumed to be identical with that specified at the location of dam failure on the Barun Pokhari. In other word, there is no attenuation loss of the GLOF on the Barun Khola.

(iii) River profile

Fig. 5-18 shows the river profile upstream of the Arun 3 dam site interpreted with 1/50,000 scale map. In order to simplify the input conditions, the Arun river slope is divided into the following five sections specifying an average gradient for each section.

Dam site	- 4 km	1/80
4 km	- 11 km	1/70
11 km	- 22 km	1/40
22 km	- 38 km	1/30
38 km	-	1/27

The critical slopes for the Arun river are calculated to be 1/16 and 1/20 for the discharges of 1,000 m^3/s and 10,000 m^3/s respectively, and no super-critical flow will take place.

(iv) Initial conditions

Water surface at Arun 3 dam : EL. 842.00 m (HWL)

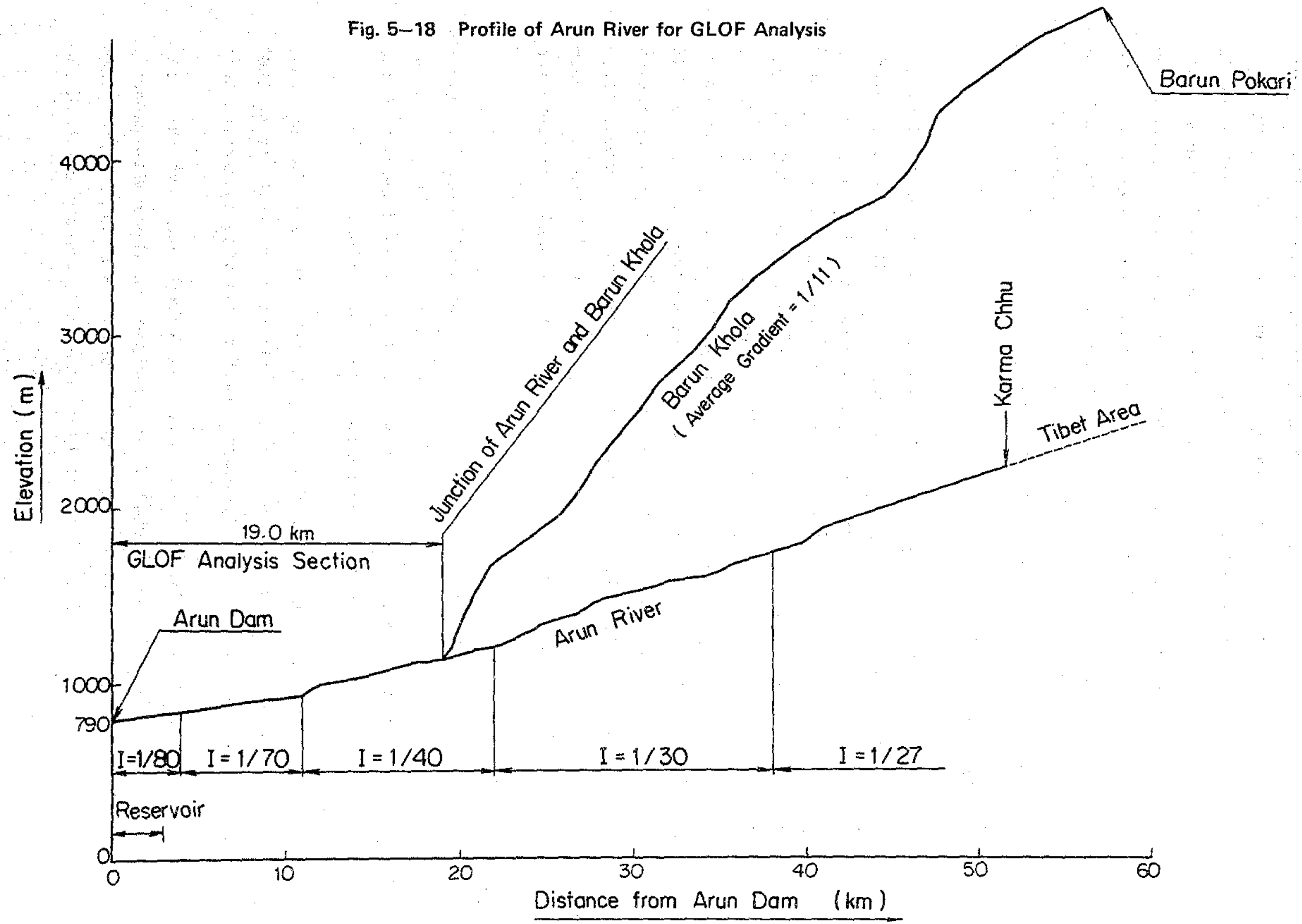
River discharge : 700 m^3/s (average value in Jun., Jul. & Aug.)

Coefficient of roughness : 0.1 (acc. to WECS report)

(v) Gate operation criteria

As the surcharge storage capacity between EL. 842.00 m (HWL) and EL. 844.00 m (design flood elevation) is approximately 1 x $10^6 m^3$ only, the capacity is too small to avoid overtopping by the assumed GLOF inflow of 1 x $10^6 m^3$ without proper gate operation in advance. In order to

Fig. 5–18 Profile of Arun River for GLOF Analysis



cope with the peak of GLOF, it is indispensable to lower reservoir surface by gate operation. Accordingly, two cases of gate operational conditions are considered in this study. In the first case, the gate is opened immediately after GLOF occurrence, while the gate is opened 30 minutes later in the second case. Both cases assume the gate hoisting speed of 0.5 m/sec. Table 5-12 indicates the discharge capacities corresponding to reservoir surface elevation and gate opening.

(3) Results of Analysis

The results of analyses for 7 cases listed in Table 5-13 are shown in Figs. 5-19 (1) - (7) and Figs. 5-20 (1) - (7). Figs. 5-19 (1) - (7) show the flood propagation (in terms of river depth and peak discharge) for the portion between the GLOF starting point (the junction of the Barun Khola with the Arun river) and the end point (the dam site). It is clearly observed that the peak discharge attenuates as it goes downstream for every cases (refer to Attenuation Line in the said figures). Except for the case 010 (in which no gate operation is assumed), the water level at the Arun dam site shows fluctuation at the elevations lower than the initial reservoir surface. This proves the effectiveness of advanced gate operation for damping the GLOF.

The details of the above movements are shown in Fig. 5-20 (1) - (7) which suggest that GLOF can be released in all cases without overtopping the dam by means of advanced lowering of the reservoir surface by appropriate gate operation.

Among the cases studied herein, Case-042 is under the severest condition, however, there will be almost no possibility of GLOF occurrence in such magnitude from the following considerations:

(i) Glacier lakes in the Barun Khola basin may have the capacity of 5 x $10^6 m^3$ at the maximum and those with capacity of 10 x $10^6 m^3$ size are unlikely. However, glacier lake with its capacity of $10^7 m^3$ size may possibly exist in the far upstream basin of the Arun river. Increase in the damage of such a large glacier lake may obviously be offset by the extension of GLOF propagation distance.

(ii) Though the time of moraine failure is presumed as 30 minutes in the study referring to the WECS report, it can be reasonably considered that the time of failure of a larger moraine dam would be longer. The initial peak discharge estimated in the study is, therefore, a conservative assumption.

(iii) It is presumed in this study that glacier lake will be completely emptied when moraine dam is breached. But this assumption is again conservative because some part thereof will not be discharged and remain there.

(iv) It is presumed that surge wave propagate with its initial form without attenuation due to the super-critical flow condition in the section between the origin of GLOF and the junction of the Barun Khola with the Arun river. However, there should be some attenuation of peak due to bends at various locations, friction loss, etc. This again makes the present assumption conservative.

(v) The gate hoisting speed of 0.5 m/min is adopted in the study, however, the higher hoisting speed will probably be applied in the extraordinary case like GLOF. With such measure, reservoir safety will be further ensured against GLOF.

In connection with the size of glacier lake stated in (i) above, only site surveys can clarify the locations and capacities. As the lake size of $10^7 m^3$ is considered to be the sort of upper limit for the moraine dam, GLOF discharge at the dam site, if it occurs, will be less than that of Case-042, even if GLOFs may take place at locations other than the Barun Khola.

Based on the present computer simulation study, it may be concluded that GLOFs occurred in the upstream basin of the Arun river can be properly disposed of by adequate operation of the spillway gates.

Table 5–12 Discharge Capacity at Various Gate Openings and Water Levels

Opening of Gate (m)	Discharge Capacity (m³/sec)													
	Water Level of Reservoir (EL.m)													
	829	830	831	832	833	834	835	836	837	838	839	840	841	842
1	98	215	287	345	394	438	478	515	550	582	613	642	670	697
2	98	283	481	610	718	813	898	976	1,048	1,116	1,179	1,240	1,298	1,353
3	98	283	529	792	969	1,122	1,257	1,380	1,493	1,599	1,699	1,793	1,882	1,968
4	98	283	529	828	1,141	1,362	1,554	1,727	1,886	2,032	2,170	2,300	2,423	2,540
5	98	283	529	828	1,176	1,527	1,786	2,015	2,223	2,414	2,592	2,760	2,919	3,070
6	98	283	529	828	1,176	1,570	1,945	2,240	2,503	2,743	2,965	3,174	3,370	3,556
7	98	283	529	828	1,176	1,570	2,008	2,393	2,721	3,016	3,287	3,539	3,775	3,999
8	98	283	529	828	1,176	1,570	2,008	2,487	2,870	3,229	3,554	3,854	4,134	4,398
9	98	283	529	828	1,176	1,570	2,008	2,487	3,007	3,374	3,762	4,115	4,443	4,750
10	98	283	529	828	1,176	1,570	2,008	2,487	3,007	3,567	3,903	4,319	4,700	5,053
11	98	283	529	828	1,176	1,570	2,008	2,487	3,007	3,567	4,164	4,456	4,900	5,306
12	98	283	529	828	1,176	1,570	2,008	2,487	3,007	3,567	4,164	4,800	5,033	5,502
13	98	283	529	828	1,176	1,570	2,008	2,487	3,007	3,567	4,164	4,800	5,471	5,632
14	98	283	529	828	1,176	1,570	2,008	2,487	3,007	3,567	4,164	4,800	5,471	6,179
15	98	283	529	828	1,176	1,570	2,008	2,487	3,007	3,567	4,164	4,800	5,471	6,179
16	98	283	529	828	1,176	1,570	2,008	2,487	3,007	3,567	4,164	4,800	5,471	6,179

Table 5-13 Input Conditions and Simulation Results for Prescribed GLOF

Case	Location of G.L.	Volume of G.L. (m^3)	Duration of Failure(min)	Start Time of Gate Operation	Initial Peak Discharge(m^3/s)	Max.Discharge from Dam(m^3/s)
010	Barun Khola	1×10^6	30	—	1,775	—
021	〃	3×10^6	〃	Just after outburst of G.L.	3,904	2,000
022	〃	〃	〃	30min. after outburst of G.L.	3,904	2,500
031	〃	5×10^6	〃	Just after outburst of G.L.	6,015	3,500
032	〃	〃	〃	30min. after outburst of G.L.	6,015	4,000
041	〃	10×10^6	〃	Just after outburst of G.L.	11,273	6,000
042	〃	〃	〃	30min. after outburst of G.L.	11,273	7,000

Fig. 5–19 (1) GLOF Propagation between Arun Dam and Junction of Barun Khola
Case–010

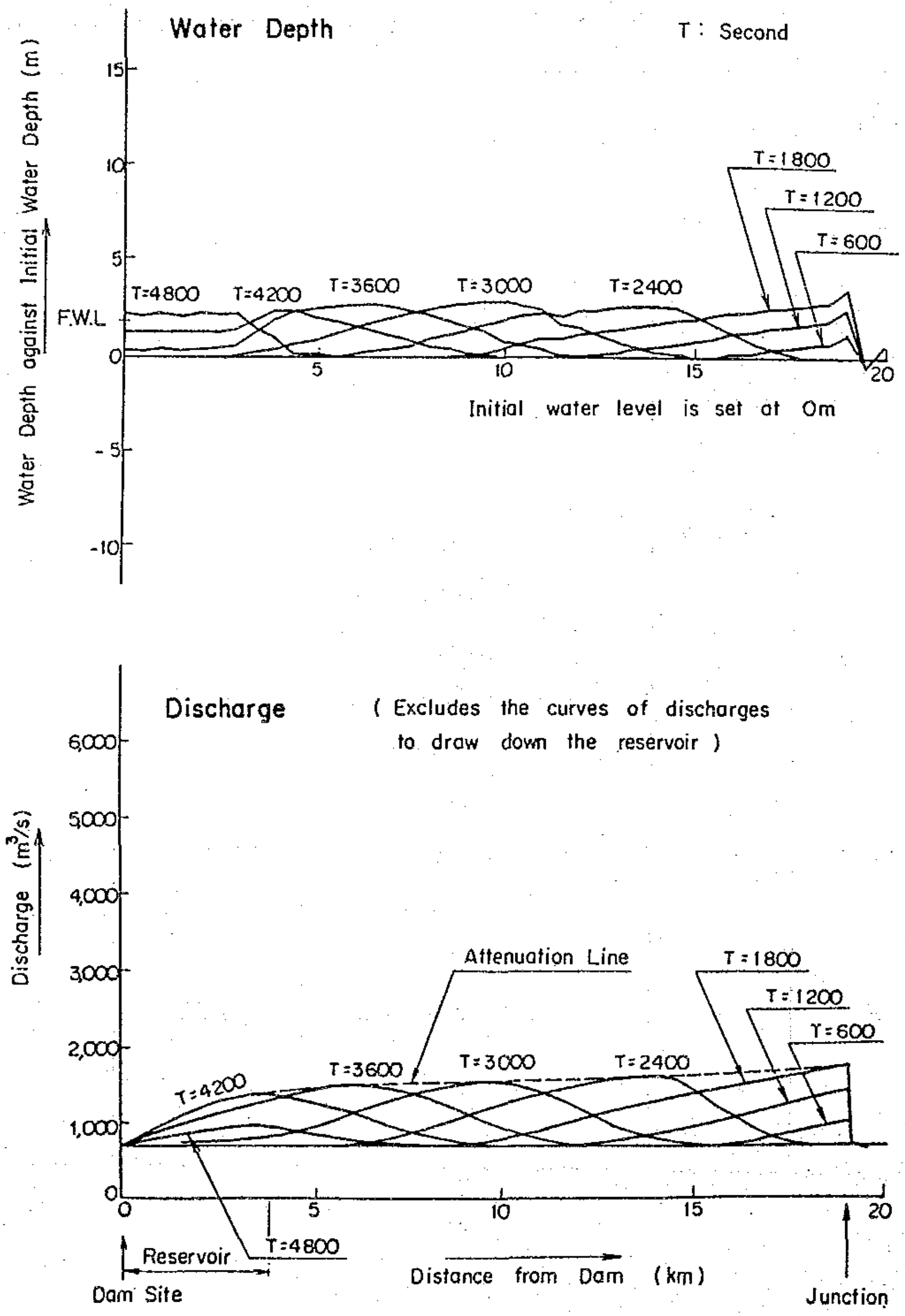


Fig. 5–19 (2) GLOF Propagation between Arun Dam and Junction of Barun Khola Case–021

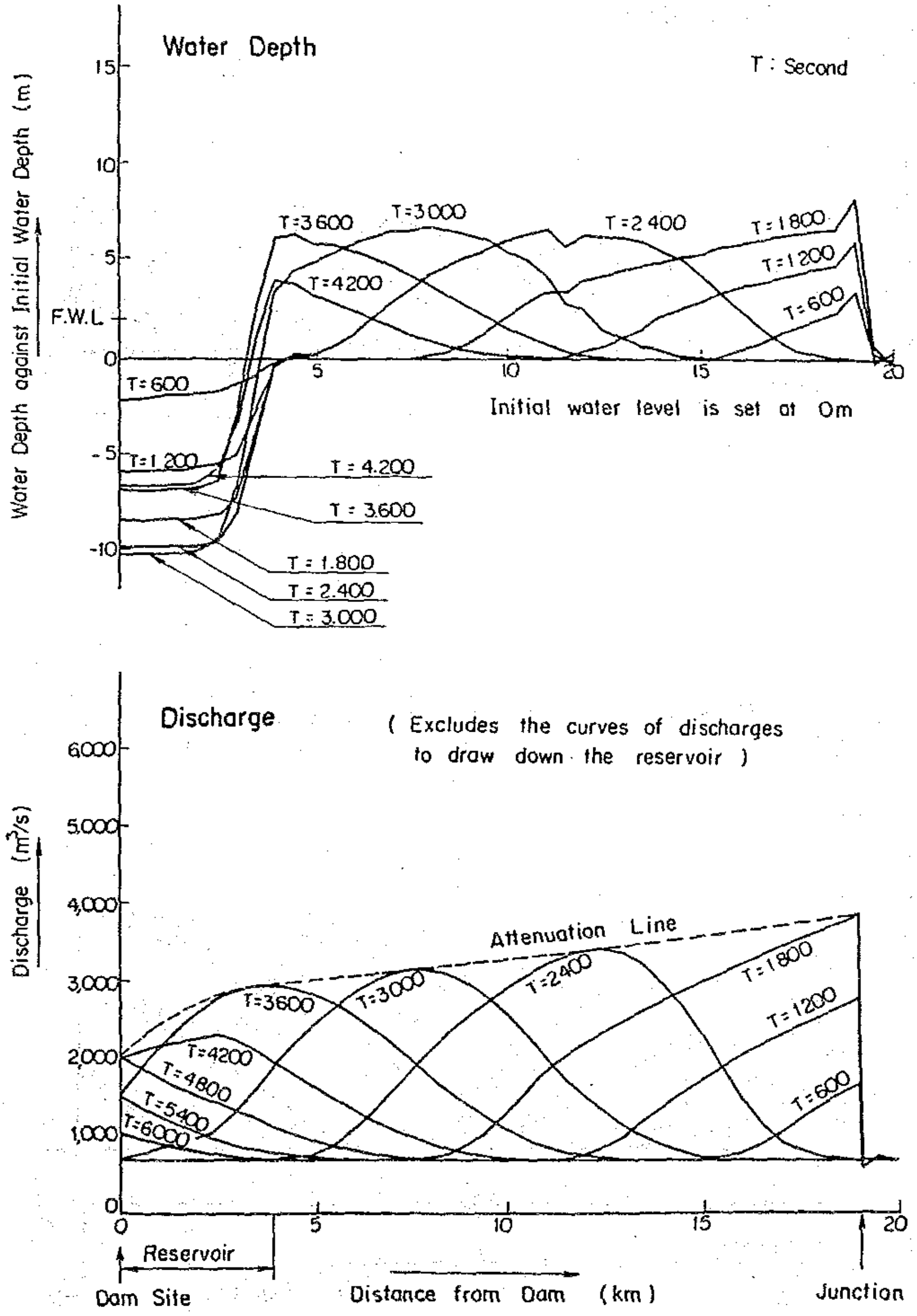


Fig. 5–19 (3) GLOF Propagation between Arun Dam and Junction of Barun Khola
Case–022

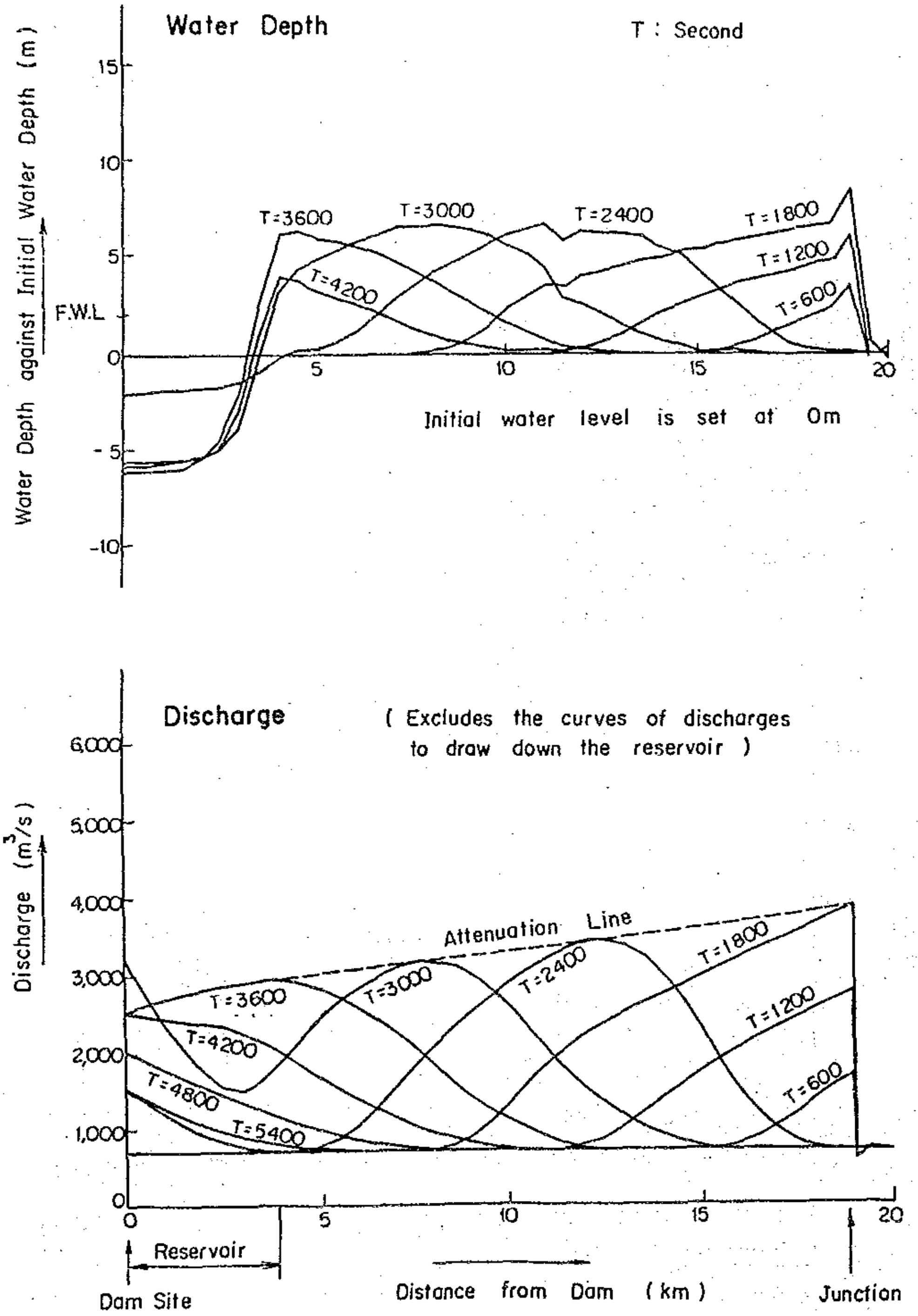


Fig. 5–19 (4) GLOF Propagation between Arun Dam and Junction of Barun Khola
Case–031

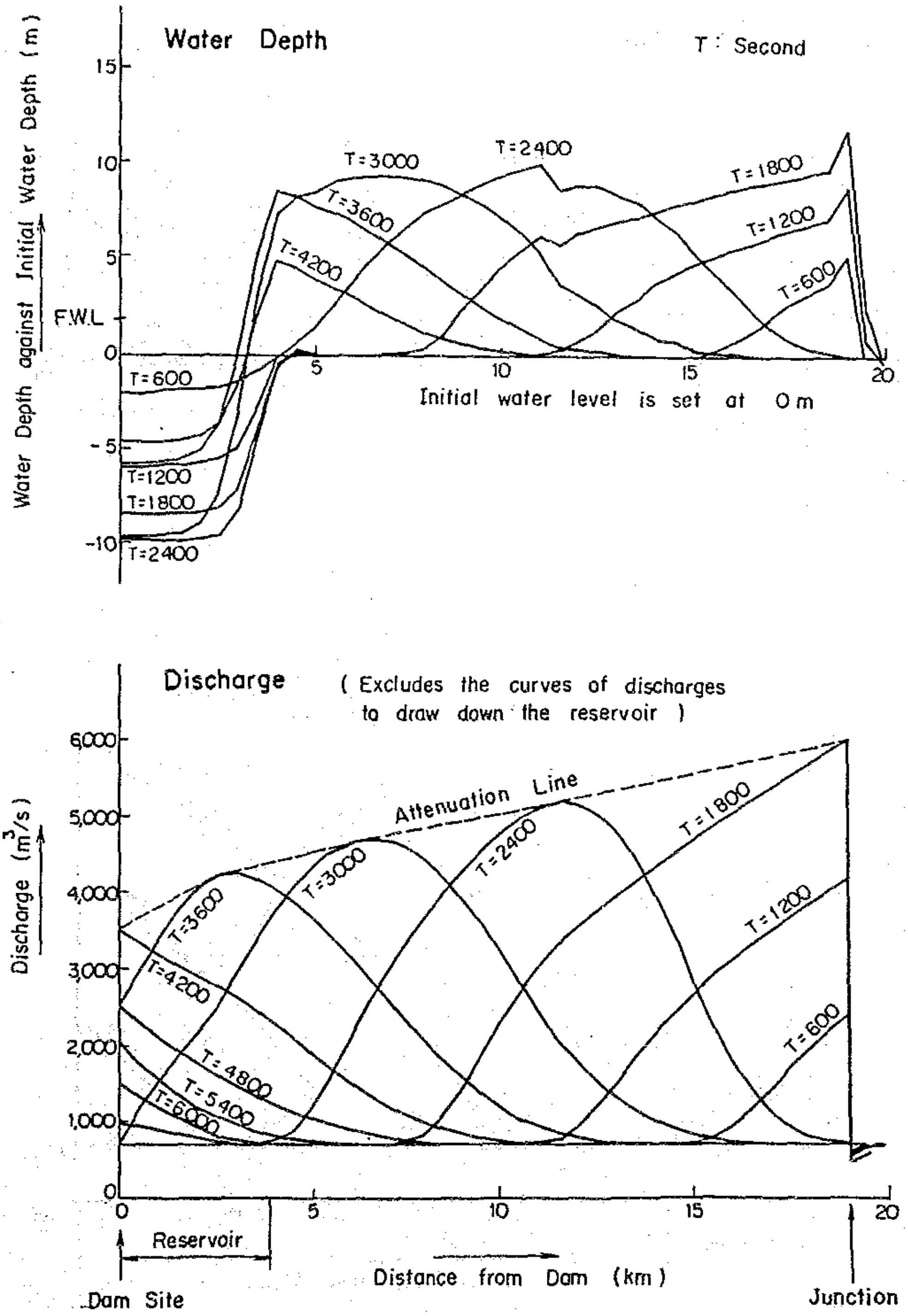


Fig. 5–19 (5) GLOF Propagation between Arun Dam and Junction of Barun Khola
Case–032

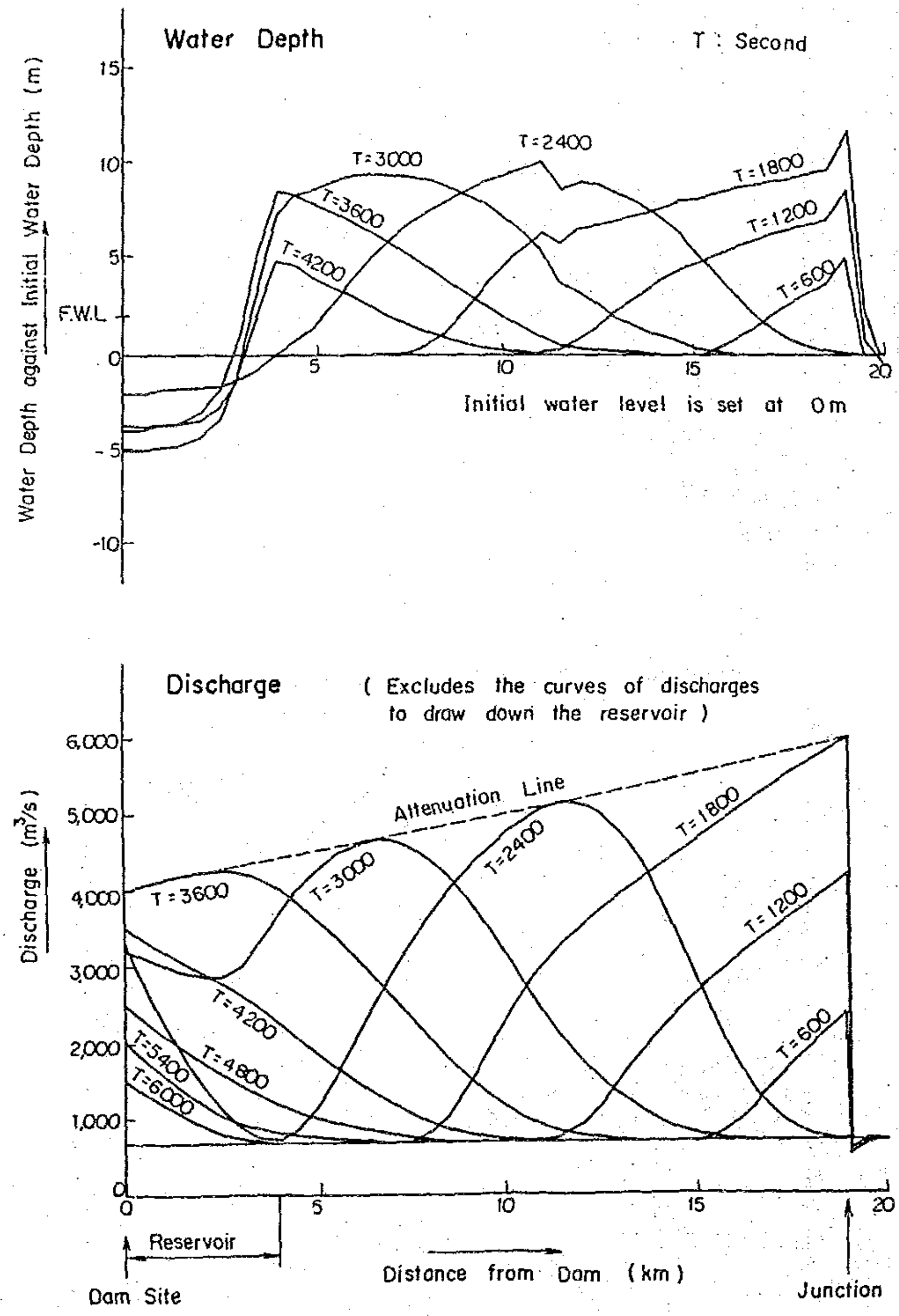


Fig. 5–19 (6) GLOF Propagation between Arun Dam and Junction of Barun Khola
Case–041

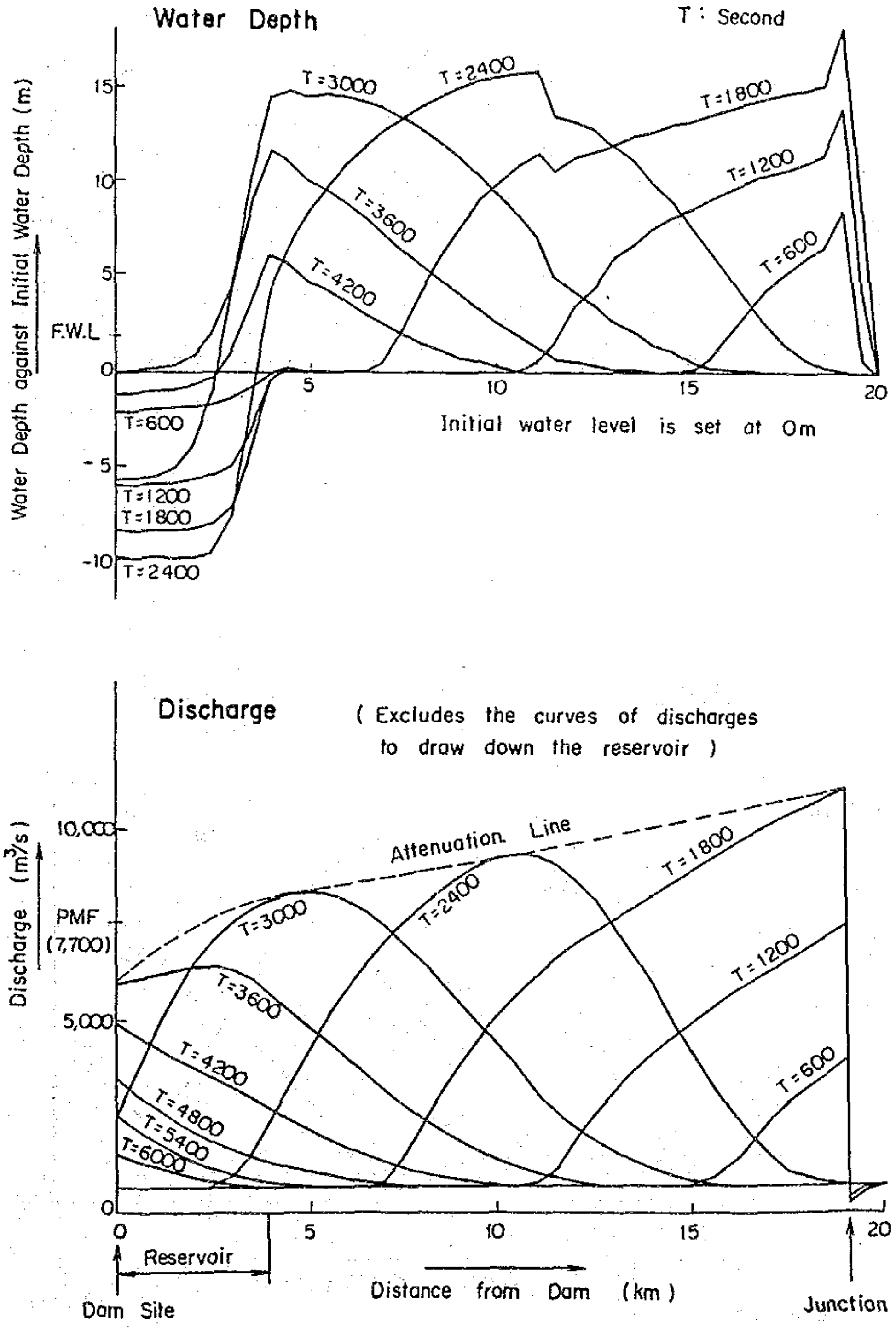


Fig. 5–19 (7) GLOF Propagation between Arun Dam and Junction of Barun Khola

Case–042

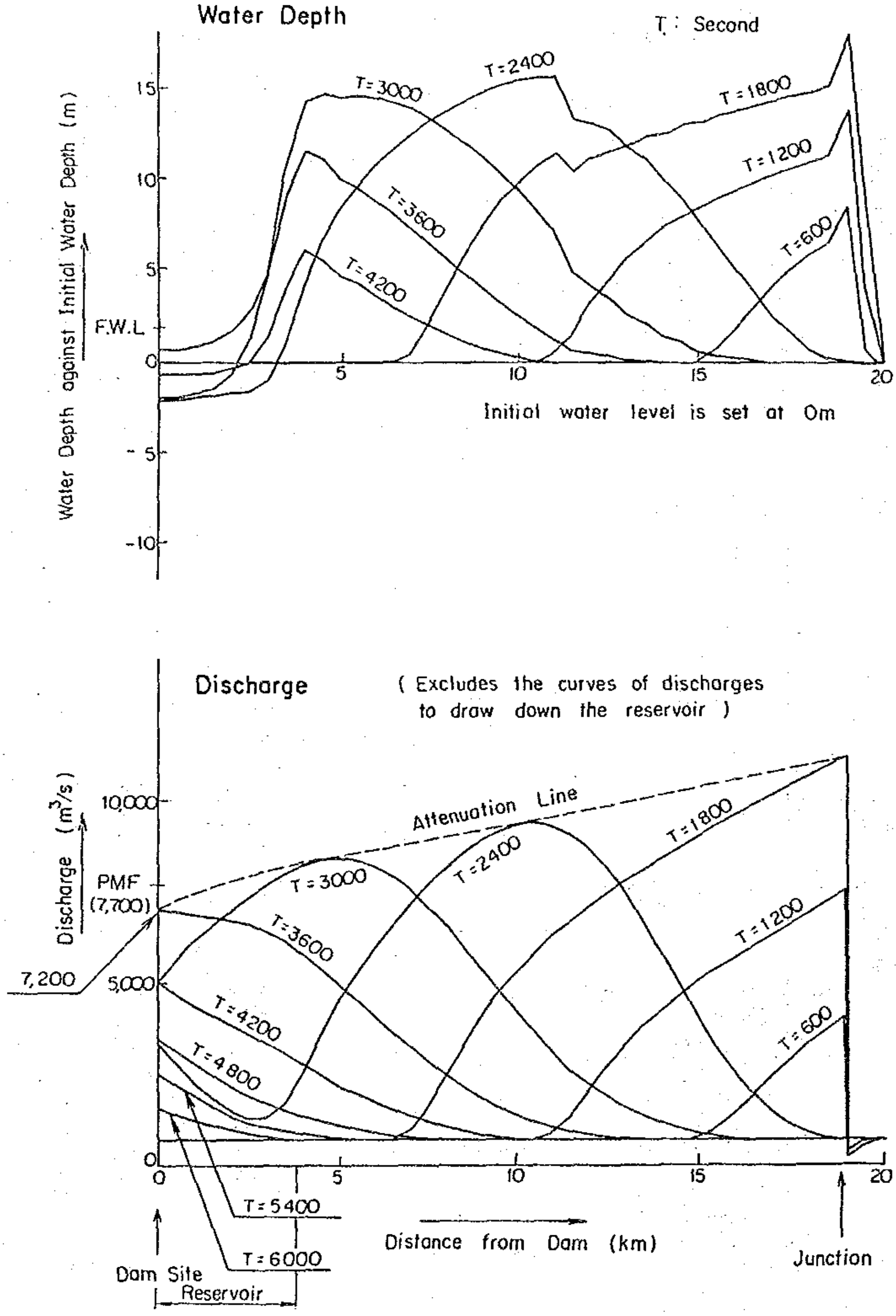


Fig. 5–20 (1) Change of Water Level in Arun Reservoir

Case–010 (No Gate Operation)

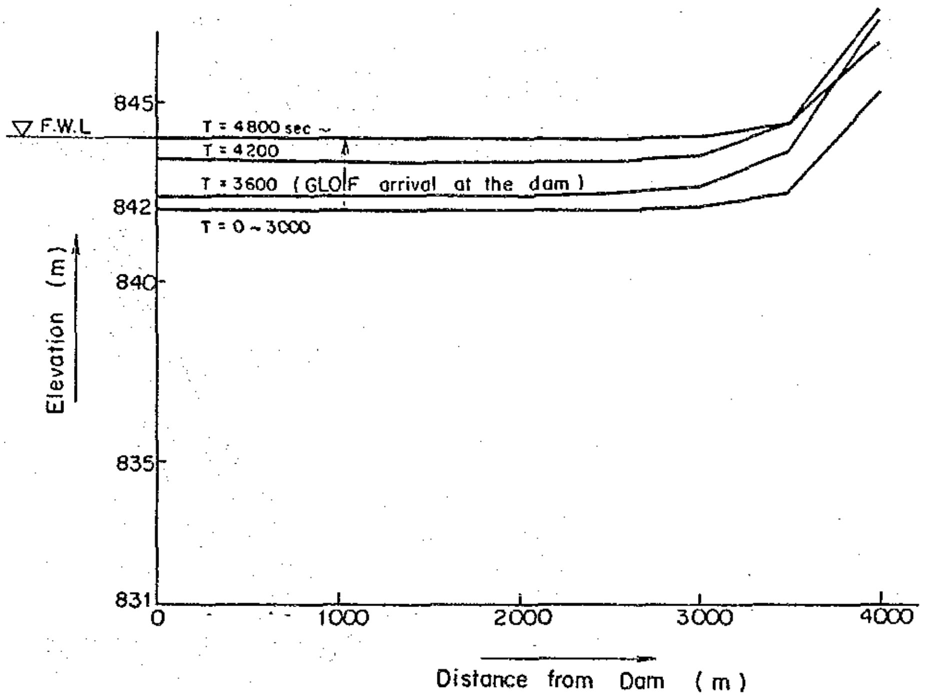


Fig. 5–20 (2) Change of Water Level in Arun Reservoir

Case–021

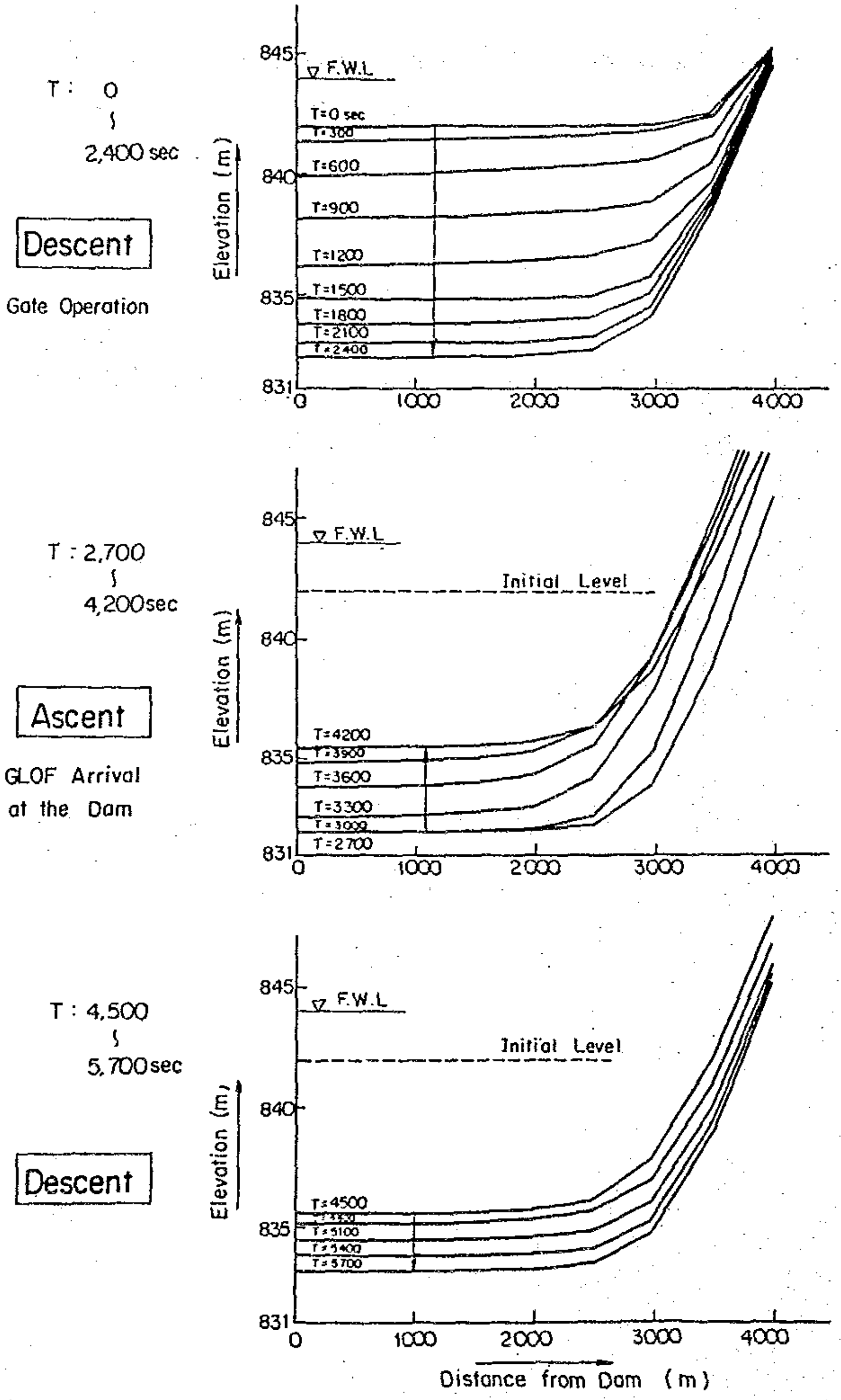


Fig. 5–20 (3) Change of Water Level in Arun Reservoir

Case–022

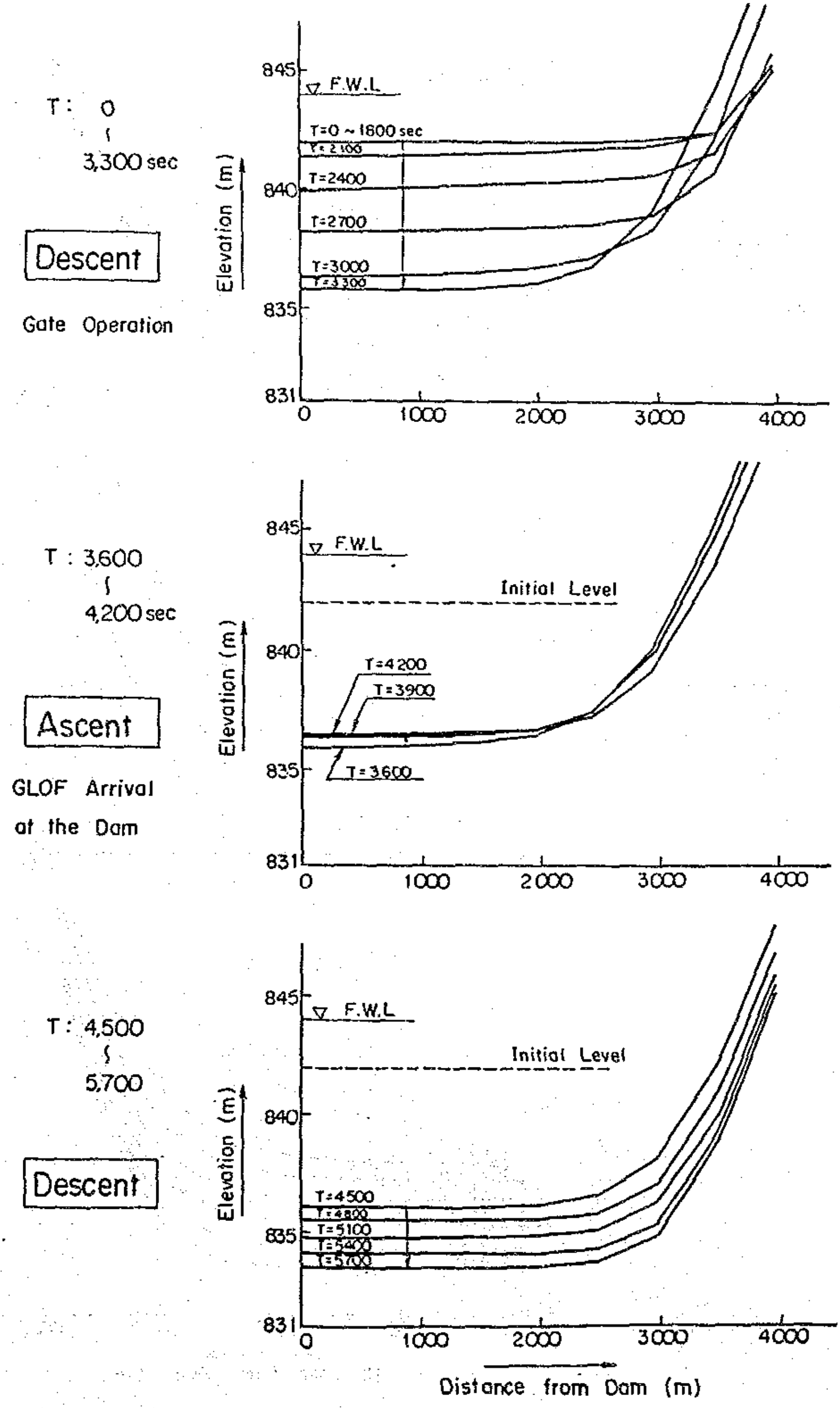


Fig. 5–20 (4) Change of Water Level in Arun Reservoir

Case–031

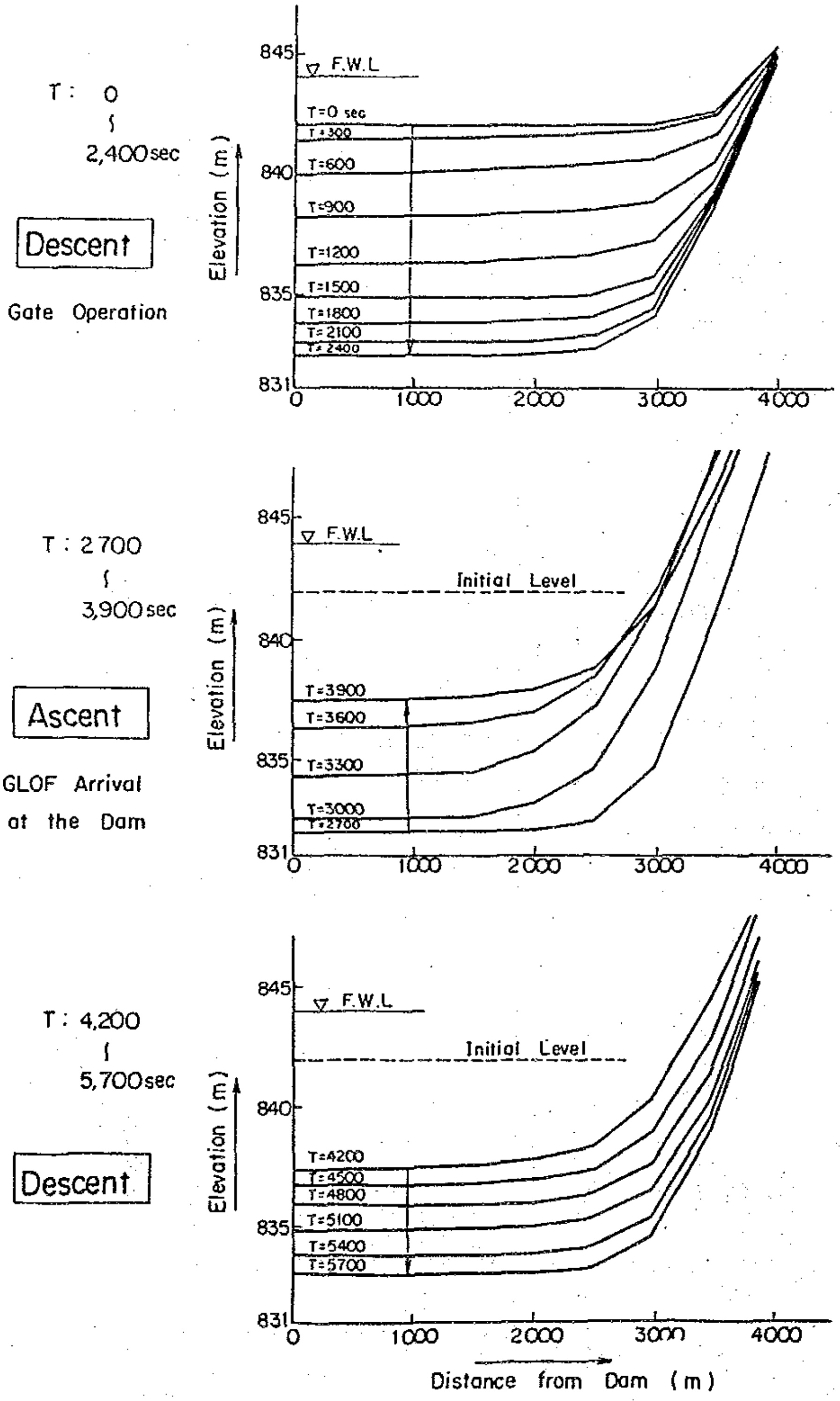
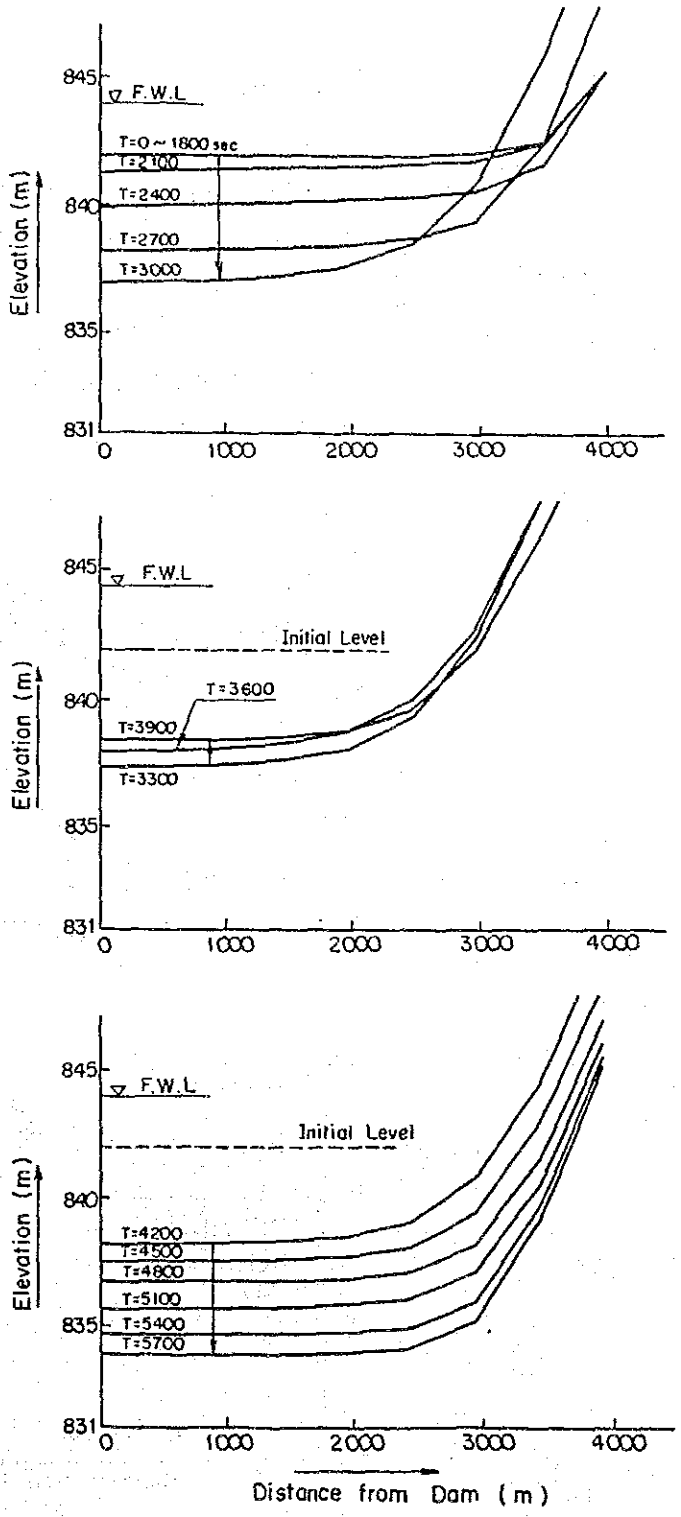


Fig. 5–20 (5) Change of Water Level in Arun Reservoir

Case–032



T : 0 ~ 3,000sec

Descent

Gate Operation

T : 3,300 ~ 3,900sec

Ascent

GLOF Arrival at the Dam

T : 4,200 ~ 5,700sec

Descent

Fig. 5–20 (6) Change of Water Level in Arun Reservoir

Case–041

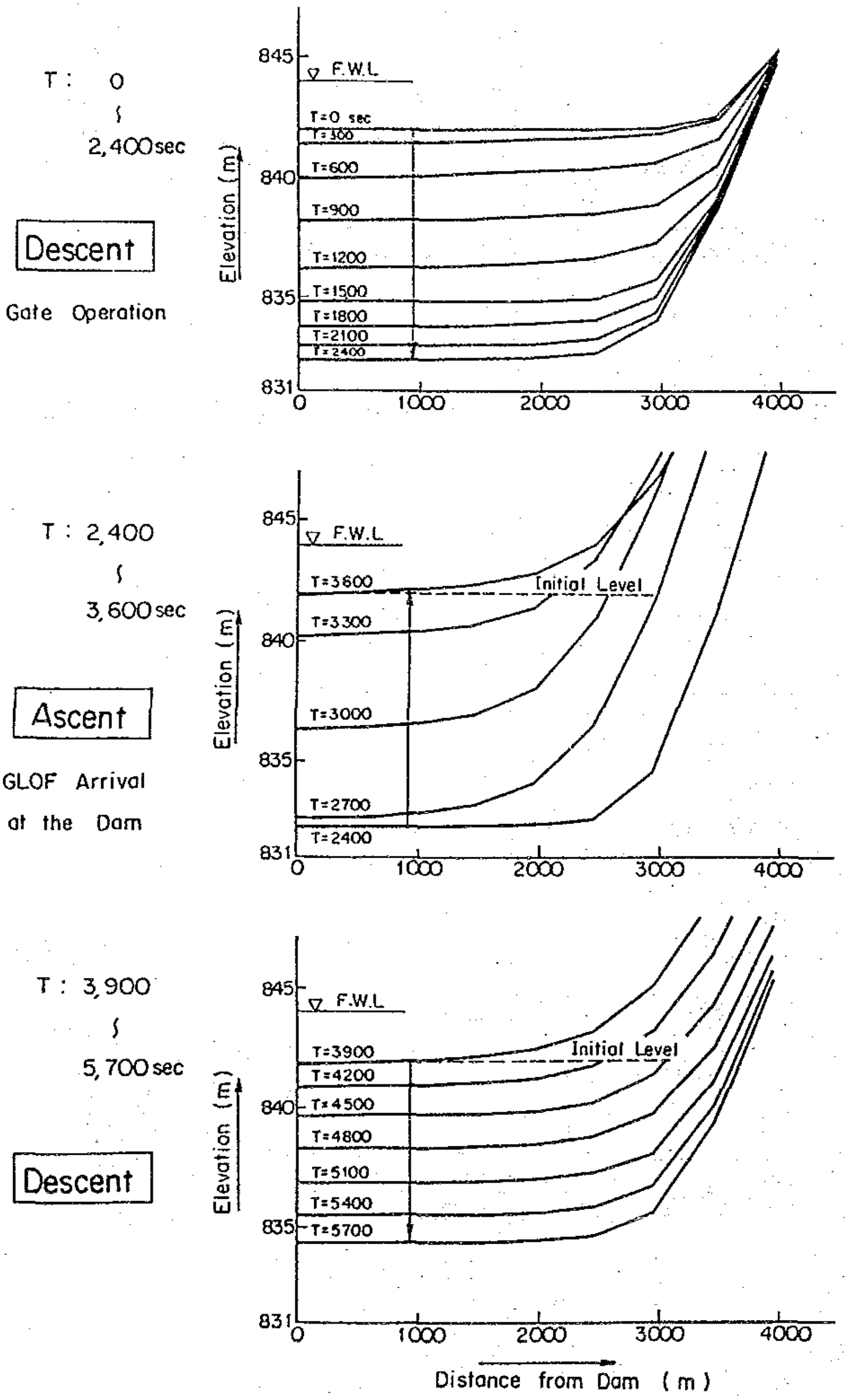
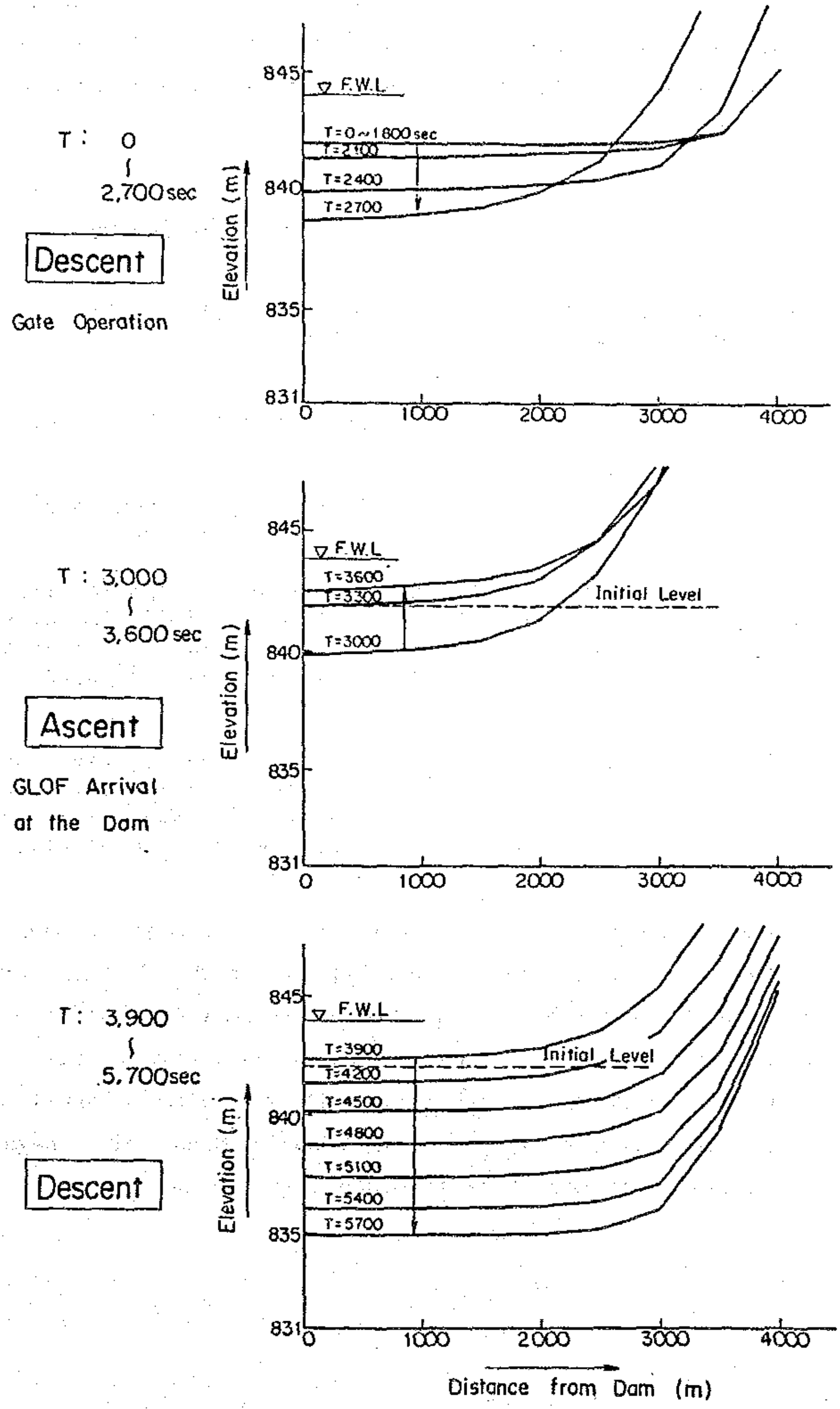


Fig. 5–20 (7) Change of Water Level in Arun Reservoir

Case–042



5.7.6 Warning System against GLOF

(1) General

To cope with GLOF, various measures such as reduction of glacier lake, construction of protective structures and also monitoring of GLOF for advance prevention of damages have to be investigated. The outline of the protective measures are shown below:

° Lowering of glacier lake surface	Controlled breaching Construction of control outlet Pumping out of lake water Tunnelling through moraine or debris barrier
° Construction of protective structures against GLOF surge	- Regulation dam for flood, high speed lifting of spillway gate, reinforced pier structure, sudden closure of intake gate
° Monitoring system	- Measurement of river surface, constant lake surveillance (by satellite and airplane), emergency communication system

Among the above, WECS' GLOF report recommended two measures that can be adequately applied in the Nepal Himalayan basin, namely, manual breaching through moraine dyke and construction of drainage facilities at the end moraine with flexible materials such as gabions. It was also advised that the possible damages could be avoided by means of a regular surveillance system at dangerous glacier lakes.

(2) Protective Measures for Arun 3 Project

In order to cope with GLOF in the Arun river basin, it can be said that one of the most effective measures is to lower the water level of a GLOF prone glacier lake. However, in the Himalayan area, such glacier lakes are situated at high altitudes making it quite hard to execute the works including transportation of materials for lowering the lake surface elevation. Then, the important element in protecting the river constructions like dam from damages by GLOF is to first provide gauging stations, sensors, etc. in the upstream basin and then to directly connect these facilities with the gate operation system for data transmission, so that the reservoir water level can be lowered prior to the arrival of GLOF surge in order to prevent overtopping as stated in 5.7.5. A close international communication system will be specially needed to cope with GLOF that may take place in China. It will also be necessary to have a regular surveillance system during monsoon season at glacier lakes with failure potential.

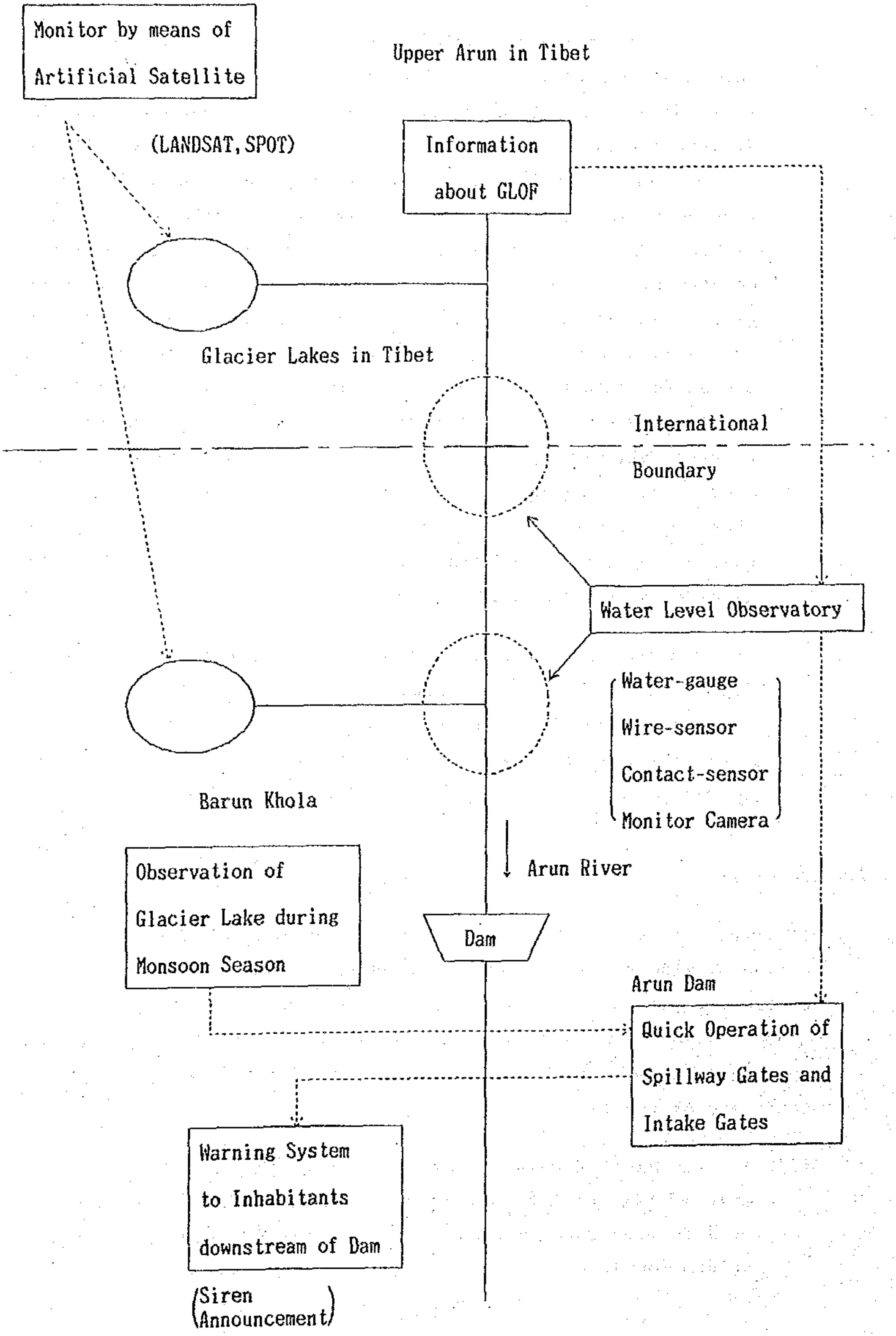
The above-stated warning system may be schematically shown in Fig. 5-21. The system shown in this figure is an example, however, it can be said at any rate that the multi-redundant observation system may be the most economically justifiable answer for ensuring the project safety against GLOF.

5.7.7 Conclusion

In connection with GLOF, its historical records, mechanism, distribution of glacier lakes, simulation analysis and recommended warning system are presented in the preceding sections. As the GLOF phenomenon is not well understood yet, it seems rather difficult to set up satisfactory countermeasures. The main findings cleared by this study are as follows.

(i) In the Nepal Himalayan area including the Arun river basin, most of glacier lakes are considered to be formed by moraines or ice-cored moraines, and glacier lakes formed by ice dam are seldom found.

Fig. 5–21 Warning System against GLOF



(ii) In the Arun river basin, GLOF (likely occurred in Tibet) was recorded around 1964.

(iii) Failure speed of a moraine dam varies in the range from several ten minutes to several hours.

(iv) GLOF generally entrains huge amount of debris, however, no report related with its volume is available and the method of quantitative analysis of the entrained debris is not established at present.

(v) Glacier lakes identified on the available maps in the Arun river basin of Nepal are located at upper reaches of the Barun Khola and Iswa Khola with an estimated capacity of 5 x $10^6 m^3$ at its maximum.

(vi) In China, there will possibly exist several glacier lakes on the Karma Chhu and also, glacier lake of $10^7 m^3$ capacity at further upstream basin of the Karma Chhu. Accordingly, it is desirable to enhance the accuracy of the studies utilizing the images of LANDSAT, SPOT, etc. and also to undertake field investigations with cooperation of China. Though the study is limited to the Arun river basin near the dam site only, it will be necessary to cover all of the Arun river basin.

(vii) According to the simulation analyses, it is found, even in the case of a large GLOF of $10^7 m^3$ size, that no harmful effects on the dam structure will be made by means of detecting GLOF occurrence in advance (30 minutes before peak surge arrives at the dam site) followed by immediate lowering of reservoir surface. The maximum discharge to be released in this case is conservatively estimated at approximately 7,000 m^3/s which is smaller than the design flood discharge of 7,700 m^3/s as described in 5.6.

(viii) Since a control of GLOF occurrence is technically and economically unfeasible at present, it is recommended for this project that relevant GLOF monitoring system will be established as an integrated part of the project. Considering the large part of the Arun river basin on the Chinese side, it is indispensable to have close cooperation from China in the area of surveillance of GLOF prone glacier lakes and monitoring river flow in its territory.

5.8 Sedimentation

5.8.1 General

The rivers like the Ganges which take rises from the Himalayan range generally contain considerable amount of suspended load and sedimentation caused therefrom is the serious problem at all the existing reservoirs. The ground of the above will be the composite action of geological deterioration due to violent orogenic movement of the Himalayan range and erosion in the downstream area due to heavy rainfall during monsoon season. In addition to the natural erosive action stated above, the artificial forest denudation will also be a factor of increase in wash load.

The Sapt Kosi river, one of the major branches of the Ganges, is containing large amount of suspended load expressly and its annual amount of suspended load per square kilometer is reported as approximately 2,000 m^3/km^2/year which will be ranked at high level in the world as per the Summary of Erosion Data in Nepal released by the Dept. of Soil and Water Conservation. It is reported that, among the major branches of the Sapt Kosi river, the Tamur river contains the maximum amount of suspended load followed by the Sun Kosi and the Arun river and that the amount of suspended load contained in the Arun river is rather small compared with those in the other rivers. This will owe to the fact that the most of the drainage basin of the Arun river is in the Tibetan area where comparatively small amount of suspended load is being produced.

The studies made in this paragraph consist of three parts; the estimate of annual suspended load at the dam site in accordance with the samples collected in the field; the cross-examination based on the measurement records in both Tibet and Nepal; the conjecture of deposit shape by simulation analysis and on the basis of the result, the way of flushing of sediment load after completion of the Arun 3 dam.

5.8.2 Estimate of Sediment Load according to Collected Data

As stated in 3.5.3, 10 samples were collected near the dam site for the purpose of water analysis. As the river discharges measured at the Tumlingtar gauging station are shown in the said table, the river discharges at the dam site are calculated with conversion coefficient of 0.76 (refer to 5.5.3) and the relation between suspended load and river discharge is given by the following equation approximately.

$$qs = 0.00045\ Q^{2.16} \qquad \gamma = 0.90$$

where, qs = Suspended load (mg/ℓ)

Q = River discharge at dam site (m^3/s)

Then, the following formula gives the annual suspended load.

$$Q_s = \sum_{i=1}^{365} (Q_i \times q_{si} \times 86{,}400)$$

$$= \sum_{i=1}^{365} (Q_i \times 0.00045 \times Q_i^{2.16} \times 86{,}400)$$

where, Qs = Annual suspended load (g)

Qi = River discharge on the day(i) at dam site (m^3/S)

qsi= Suspended load on the day(i) at dam site (mg/ℓ)

The results of calculation are as shown in Table 5-14 below.

Table 5–14 Annual Suspended Load Concentration

Unit: 10^3 ton

Year	Qs	Year	Qs
1975	5,293	1981	10,184
1976	4,717	1982	3,009
1977	6,412	1983	5,337
1978	5,356	1984	4,220
1979	6,654	1985	4,614
1980	18,118	Average	6,719

The average annual suspended load per unit area will be obtained by means of the above average value in the table divided by the total drainage area as calculated below.

$$6{,}719 \times 10^3 \text{ ton}/29{,}310 \text{ km}^2 = 229 \text{ t/km}^2\text{/year}$$

It is necessary to estimate the bed load for estimate of the deposit in the reservoir and 20 percent is adopted in this study. In connection with the ratio of trapped sediment to the reservoir capacity, the figure deviced by Brune is generally applied. According to this figure, the capacity-inflow ratio for the gross reservoir capacity of $11.2 \times 10^6 m^3$ versus annual inflow of approximately $10{,}000 \times 10^6 m^3$ is given to be only 0.1%, which indicates that the most of suspended load flows down through the dam without being trapped, and the ratio of 0.2 is tentatively applied in this study. Thus, the annual sediment will be given as calculated below.

$$6{,}719 \times 10^3 m^3 \times (1 + 0.2) \times 0.2 = 1{,}613 \times 10^3 \text{ ton/year}$$

and assuming specific gravity of 1.4,

$$1{,}613 \times 10^3 \text{ ton}/1.4 = 1{,}152 \times 10^3 m^3\text{/year}$$

Assuming that the annual deposition will progress at the rate of the above amount year by year, the surface of deposit will reach the crest elevation of the overflow section (EL. 828.00 m corresponding to reservoir capacity of approx. $4.5 \times 10^6 m^3$) in 4 years after impounding. However, it will be adequate to express that the deposit will reach the crest elevation in several years without defining as 4 years, as no effective measures concerning the capacity-inflow ratio is available at this stage.

5.8.3 Record of Suspended Load in Neighboring Basin around Arun River

Since the most part of the Arun river basin is in Tibet, the Arun river takes on a different character concerning suspended load compared with the other branches of the Ganges river. The annual suspended load concentration of 229 $\text{ton/km}^2\text{/year}$ of the Arun river is one place smaller than those of the other branches and this will indicate that the amount of suspended load originated in Tibet is far smaller than that produced at the southern slope of the Himalayan range.

Tables 5-15(1) and (2) show the suspended load contained in the Sapt Kosi river and the rivers in Tibet. According to these figures, the average annual suspended load of the Sapt Kosi river is estimated at 1,800 m^3/km^2 equivalent to approximately 2,500 ton/km^2 and that of the rivers in Tibet is 127 ton/km^2 and the ratio of these two is counted to be almost 20 times.

Such big amounts of suspended load contained in the rivers originating from the Himalayan range are caused by the combined effects of violent orogenic movement, abundant precipitation and artificial forest denudation as previously stated.

While, the main reasons of small suspended load contained in the river in Tibet will be mainly attributed to small precipitation, inactive erosion due to gentle river slopes and small population requiring less cultivated farm land. Further, the factors that there is no possibility of flood which will transport the large amount of sand materials due to small precipitation and most of the river discharge originates from underground water, etc. will also be the causes.

Following shows another estimate of suspended load at the Arun 3 dam site.

Drainage area	:	27,929 km^2 (Tibet)
	:	1,381 km^2 (Nepal)
Annual suspended load	:	127 ton/km^2 (Tibet)
	:	2,500 ton/km^2 (Nepal)

Then, the annual suspended load at the dam site will be,

$$\frac{127 \times 27,929 + 2,500 \times 1,381}{27,929 + 1,381} = 239 \text{ ton/km}^2$$

Table 5-15 (1) Sedimentation Load of Sapt Kosi River

River	Catchment Area (㎢)	Annual Sedimen-tation Load (㎥)	Annual Sedimentation Load per km^2 (m^3/㎢)
Sun Kosi	19,000	54×10^6	2,840
Arun	36,000	35×10^6	970
Tamur	6,000	30×10^6	5,000
Sapt Kosi	61,000	110×10^6	1,800

Source : Summary of Erosion data in Nepal, FAO/UNDP, Dep. of Soil and Water Conservation

Table 5-15 (2) Sedimentation Load of Rivers in Tibet

River	Catchment Area (㎢)	Annual Sedimen-tation Load (㎥)	Annual Sedimentation Load per km^2 (m^3/㎢)
Jinsha Jiang	187.507	15.7×10^6	84
Lancan Jiang	84,220	20.7×10^6	246
Nu Jiang	118,760	19.6×10^6	165
Yarlung Zangbo	106,378	14.5×10^6	136
Yarlung Zangbo	189,843	19.0×10^6	100
Nyang Qu	6,216	0.9×10^6	145
Lhasa He	26,225	1.0×10^6	37
Total	719,149	91.4×10^6	(Average) 127

Source : Rivers and Lakes of Xizang

Compared with the value of 229 ton/km^2/year calculated on the basis of the samples collected as described in 5.8.2, this calculation gives almost same figure, hence, these calculations are proved to be reasonable and acceptable.

5.8.4 Conjecture of Deposit Shape

The approximate value of the deposit in the reservoir is estimated as per the above paragraphs and the following indicates the results of simulation analysis to conjecture the shape of deposit. (EPDC/KCC FLOW 700 MODEL)

(1) Calculation Process

(i) Non-uniform flow calculation for the initial river sections

(ii) Calculation of friction velocities (U*) at respective sections

(iii) Calculation of sediment load by particle sizes with the Lane-Kalinske formula and estimate of total load

(iv) Estimate of riverbed movement by equation of continuity and then surface elevation of deposit

(v) Repeated calculation of the above on daily basis

(2) Prerequisite for Calculation

(i) Grading curve

Grading curve used is based on the results of sieve analysis of river deposit collected at the dam site (See Appendix A.3). However, it is assumed that the major component forming continuous deposit throughout the year will be suspended load, hence, the calculation is made considering the particles of smaller than 1.1 mm having the following distribution.

Size (mm)	1.1	0.54	0.37	0.23	0.14
Distribution (%)	10	20	40	20	10

(ii) River discharge

The calculation is made from January 1, 1975 with the river discharge at the dam site described in 5.5.3.

(iii) Reservoir elevation

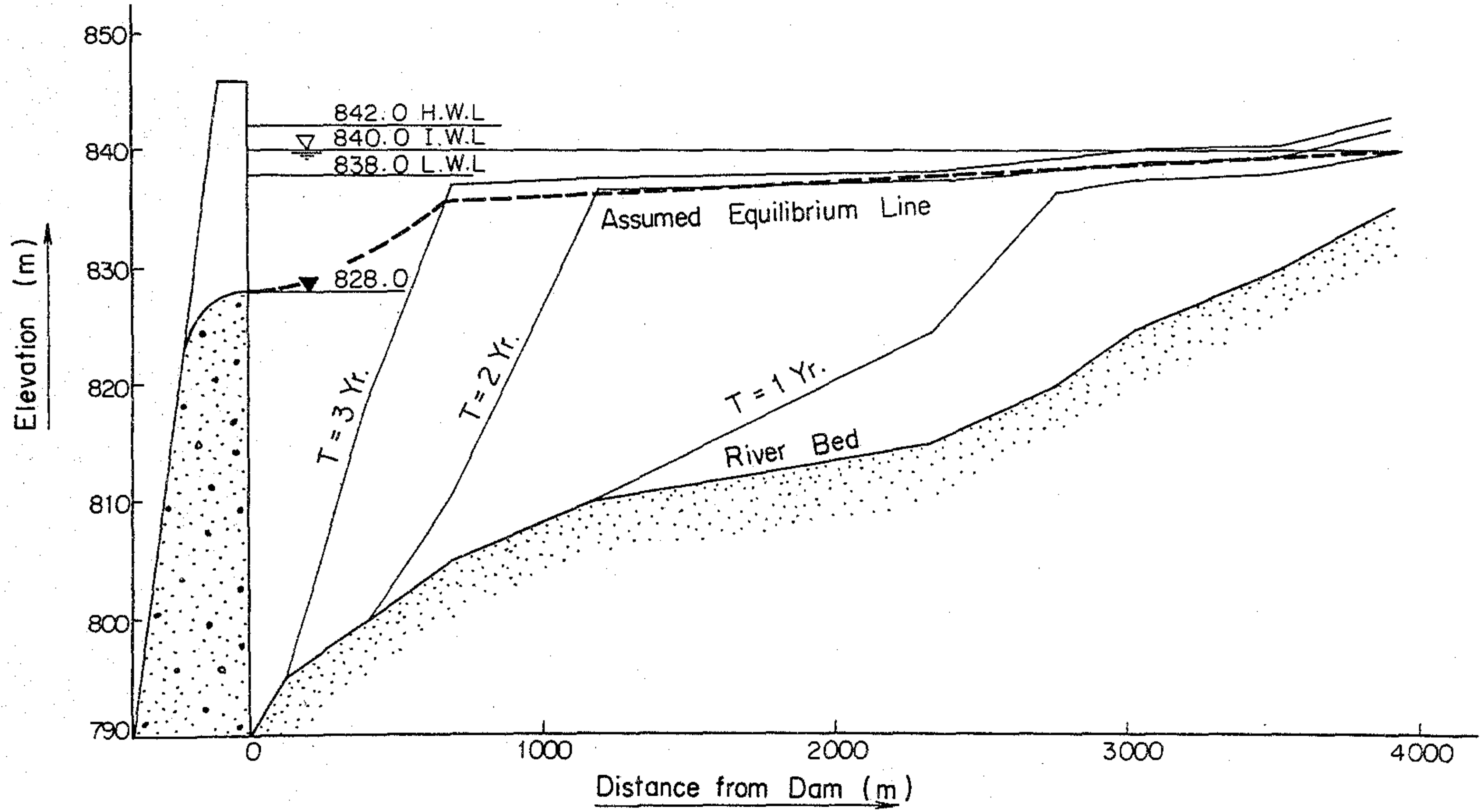
The reservoir surface used for calculation is set at EL. 840 m.

(3) Result of Calculation

According to the result of calculation shown in Fig. 5-22, it is considered that the front of deposit will reach near the dam site in three years. Further, as the effective storage capacity will be decreased by deposit at the upstream end of the reservoir, it is required to move the said deposit into the reservoir by adequate flushing operation.

Since spillway gates equipped at the Arun 3 dam are operated throughout the period of wet season, it is considered that the surface of deposit will keep equilibrium at the dotted line shown in the said figure, still it will be required to perform flushing operation every year in order to remove the deposit at the upstream end of the reservoir which will be formed continuously.

Fig. 5–22 Reservoir Sedimentation Profile



CHAPTER 6 . ALTERNATIVE SCHEME

CHAPTER 6. ALTERNATIVE SCHEME

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CHAPTER 6. ALTERNATIVE SCHEME

6.1 Study on Alternative Layout

6.1.1 General

The objective of this chapter is to make studies on the alternative locations and arrangements of civil structures such as dam site, intake water level, desanding basin and headrace tunnel arrangement, powerhouse site, etc. and to select the basic layout to be applied to the optimization study in Chapter 7. In selecting the basic layout, it is also necessary to make the similar studies on access road, powerhouse equipment, transmission line and substaion facilities, etc. other than the above components, however, these studies are not included in this chapter as they are described in detail in Chapters 8,9 and Volume II (Access Road). It is noted that the input data for the optimization study in Chapter 7 include those related to these items.

6.1.2 Study on Alternative Layout

Prior to this study, two separate studies were made in relation to this project. The Master Plan Study by JICA for utilization of water resources of the Kosi river basin identified this Arun 3 project to be most attractive out of 52 sites. To follow up this study, the Prefeasibility Study on the project was carried out by the then Electricity Department. These two studies, although of different level, had different alternative schemes proposed. In the Master Plan Study, a powerhouse of 240 MW capacity with its location at Solakhani and headrace tunnel of 7.1 km long was envisaged. A detailed comparison was made in the subsequent Prefeasibility Study for different alternative schemes including that of the Master Plan Study. The 400 MW capacity scheme with powerhouse located at the Kaguwa site with headrace tunnel of about 11.4 km long was judged as the best alternative among different alternatives.

The outline of the project shown in the Master Plan Study and the Prefeasibility Study are shown in Table 6-1.

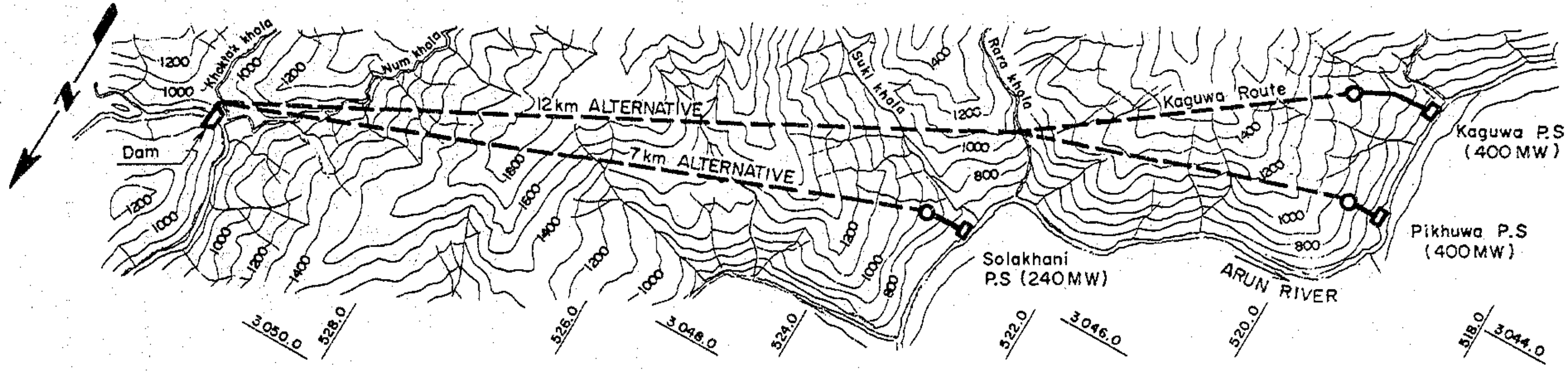
Table 6–1 Outline of Projects shown in Previous Reports

Item		Master Plan	Pre F.S.
Catchment Area	(km^2)	32,332	30,031
Regulating Pondage			
HWL	(ELm)	810	840
Available Drawdown	(m)	0	4
Capacity 10^6m^3		0	1.4
Dam			
Type		Concrete Grav.	Concrete Grav.
Height x Length	(m)	23 x 120	54 x 125
Power Tunnel			
Type		Nonpressure	Pressure
Dia. x Length	(m)	10 x 7,100	10 x 11,300 (7x11,300x2)1/
Power Generation			
Max Discharge	(m^3/s)	156	156
Gross Head	(m)	194	308
Installed Capacity	(MW)	240	400

1/ : Figure in parenthesis is for the alternative.

In addition to the above alternatives, one more alternative having powerhouse located at the Pikhuwa site was proposed in this feasibility study. Considering the previous alternatives in different level of study and also the different locations of dam sites, re-study on these alternatives shown in Fig. 6-1 was made based on the same intake dam site (upstream dam site). Then the Solakhani site was found to be economically inferior to the other two alternatives and eliminated from further investigations and studies. In the following paragraphs, the results of analyses of dam, intake and desanding basin at different locations, tunnel layout and powerhouse site are described.

Fig. 6–1 Alternative Scheme Layout



6.2 Dam Site

Two locations have been proposed as the possible dam sites for the project. One called as the upstream dam site is located approximately 250 m upstream of the junction of the Khoktak Khola and Num Khola with the Arun river and the other as the downstream dam site is located approximately 500 m downstream of the abovementioned junction.

The riverbed width and the thickness of riverbed deposit at these dam sites are estimated to be 50 to 60 m and 10 to 15 m, respectively. However, the accurate bedrock elevation at the downstream site on the center of the river is unknown since only one vertical drill hole (DDH-1) has been surveyed at the right bank.

The riverbed elevations at these two dam sites are EL. 794 m and EL. 786 m, respectively so that the downstream site is 8 m lower in elevation.

The topographical and geological features of these two dam sites are summarized below and shown in Fig. 6-2, Fig. 6-3 and Table 6-2.

(1) The upstream dam site is located upstream of the junction of the Khoktak Khola and the Num Khola with the Arun river, so that the dam body, intake and other appurtenant structures will not be directly affected by large-scale debris flows expected to occur at the Num Khola.

(2) Even in the case of the upstream dam site, there is a landform observed at the right bank immediately upstream of the dam axis which has the possibility of landslide. However, since the elevation is 30 m higher than the proposed high water level and the predicted scale can be estimated at approximately 30 x 10^3 m^3 only, it will be easy to take countermeasures.

(3) According to the topographical conditions, the excavation and concrete volumes at the upstream dam site will be smaller than those at the downstream site when comparison is made at the same intake water levels. The rough estimate shows that in case of intake water level at EL. 840 m, for example, the volume of the dam at the upstream site will be approximately 160 x 10^3m^3, while

that at the downstream site, the volume will be 280 x 10^3 m^3, giving large difference between the two.

(4) For the same dam height at both sites, the dam volume at the downstream site will be increased by 50% over the upstream site, and moreover, there will be a loss of effective head of 8 m.

Since the technical and economic advantages of the upstream dam site was proved from various studies based on the field geological reconnaissances and investigations as well as topographic surveys, the upstream dam site was taken up in the succeeding studies and the downstream dam site was discarded.

Table 6-2 General Features of Proposed Dam Sites

	Upstream Dam Site	Downstream Dam Site
(1) Location	Approx. 250 m upstream of junction of Num Khola with Arun river	Approx. 500 m downstream of junction of Num Khola with Arun river
(2) Topography	Refer to Fig. 6-1	Refer to Fig. 6-1
° River width	° 52 m at river surface (dry season)	° 62 m at river surface (dry season)
° River deposit	° 12.5 m (confirmed by UDH-1 and UDH-6)	° 15 m or deeper (estimated by DDH-1)
° River surface	° EL.794 m (dry season)	° EL.786 m (dry season)
(3) Geology		
° Bed rock	° Hard, massive augen gneiss	° Hard augan gneiss intercalated with pegmatite, partly cracky
° Overburden	° Very thin at both banks	° Very thin at left bank, however, right bank is covered with thick talus deposit, especially at its lower portion (SLD-1, SLD-4, DL-5)
° Landslide	° Possibility at locations upstream of dam site on the main stream and Indua Khola. Magnitude would be limited.	° At upper reach of Num Khola, large surface landslide is taking place.

Fig. 6–2 Location of Dam Site

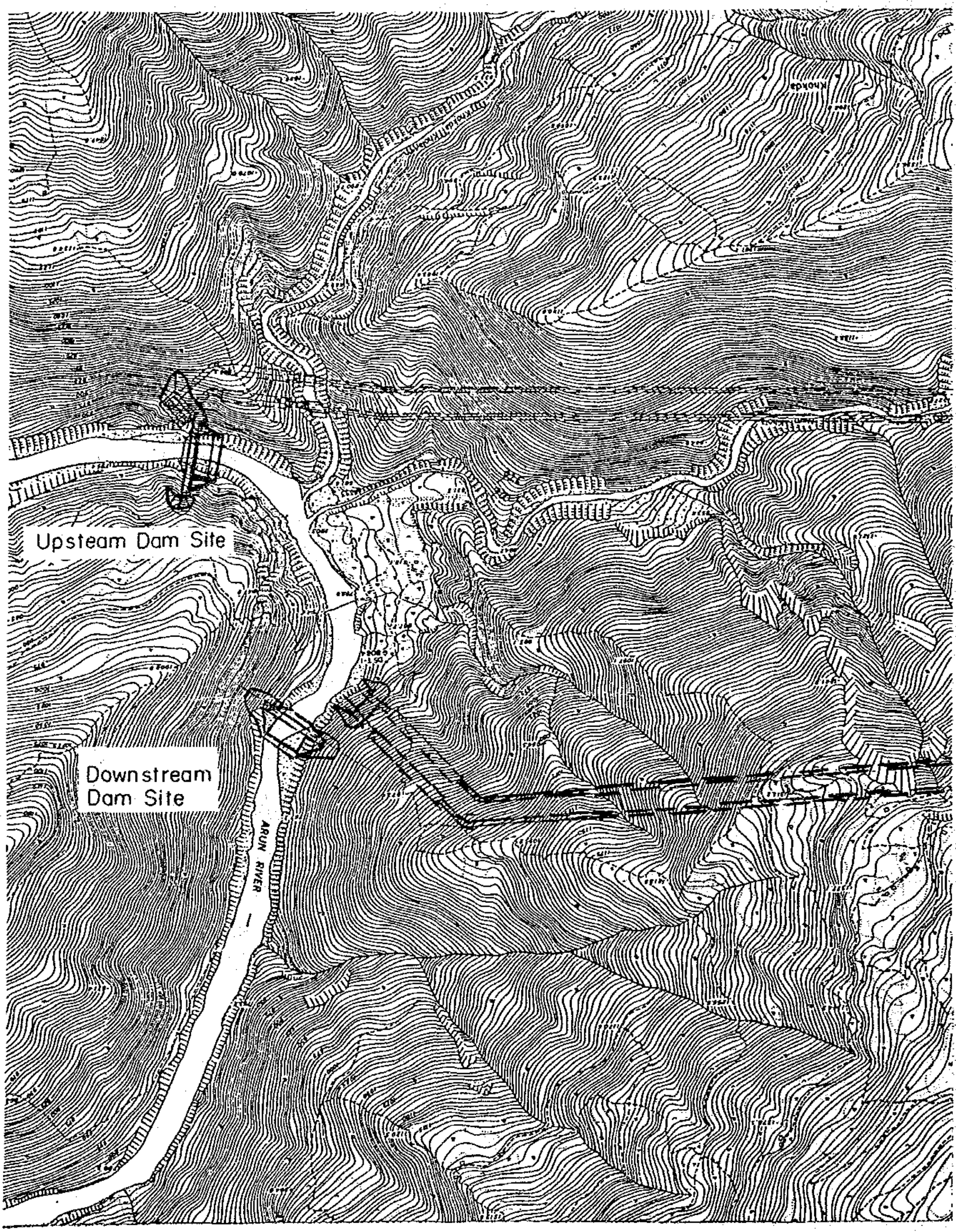
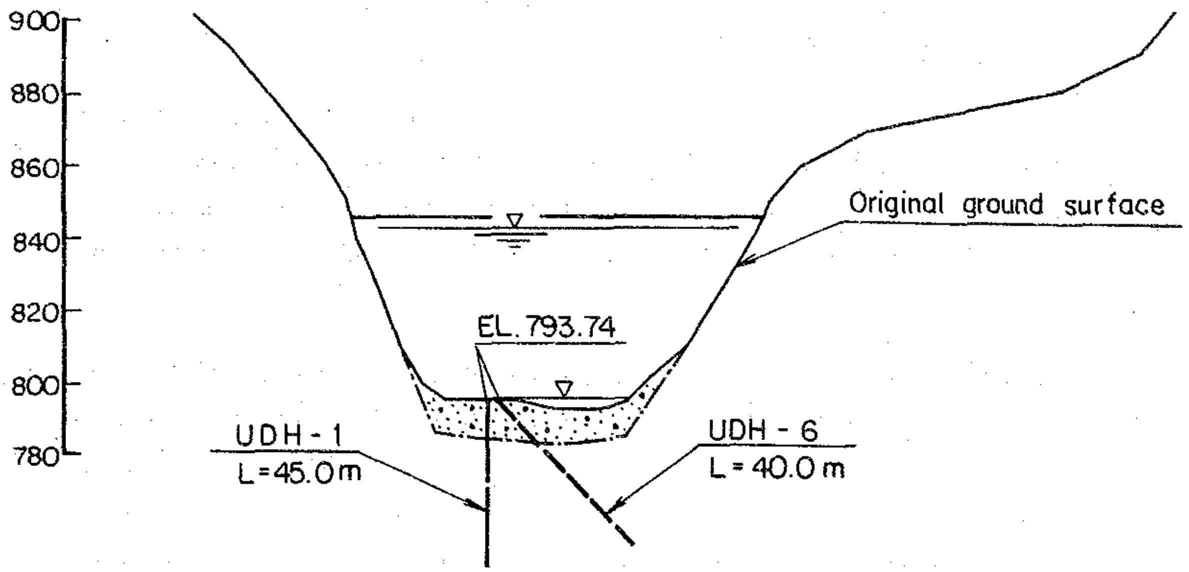
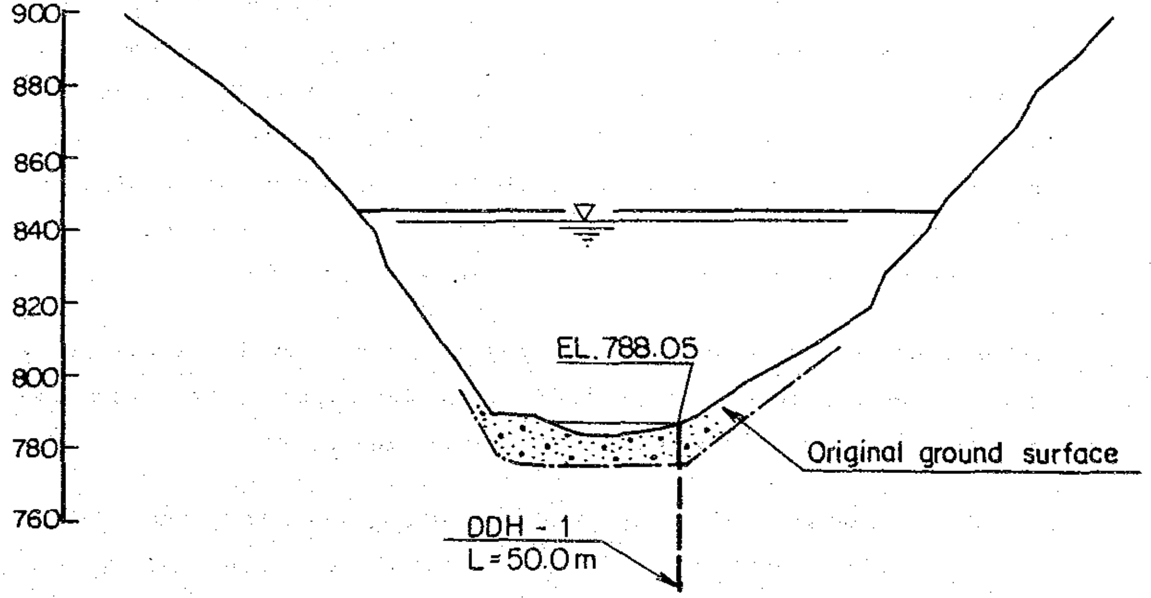


Fig. 6–3 Cross Section at Two Dam Sites

Upstream Dam Site



Downstream Dam Site



6.3 Intake Water Level

6.3.1 Intake Water Level

The selection of the intake water level will directly determine the dam height, and as shown in Table 6-1 as well as Fig. 6-4, extremely different criteria were adopted for examinations in the Master Plan Study and the Pre-feasibility Study.

In the Master Plan Study, the concrete dam is of low weir type having a height of 12 m from the riverbed. Sediment, fundamentally, is to freely overflow the weir portion and sand flush gate is provided to maintain low sediment level in the vicinity of the intake only.

On the other hand, the scheme proposed in the Prefeasibility Study is a high dam of 40 m from the riverbed (54 m from the foundation rock) to the overflow crest on which the spillway gates will be installed. To cope with sedimentation, 4 units of sand flush facilities composed of sluice gates, stop gates and conduits are to be provided. As the surface of sedimentation will always be kept at low elevation by these facilities, this dam will provide the regulating reservoir capacity which facilitates generating operation meeting the load variation.

In view of the form of load demand and the functions of the other power stations in Nepal, it is considered that the Arun 3 power station shall be provided with functions which enable peaking generation in accordance with daily load variation to some extent. Therefore, in order to be able to follow load variation, a high dam type with certain regulating capacity will be considered as the basic concept of development, instead of a lower weir.

The dam height will be decided through economic optimization study (B-C) using the intake water level as a major parameter. Advantageous points of the high dam can be summarized as follows:

(i) With provision of a certain regulating capacity, the peaking generation complying with load variations can be easily done enhancing the economic superiority of the project (Refer Chapter 7, Fig. 7-6).

(ii) An additional head of 20 to 30 percent of the topographically obtainable natural head can be created so that project economy can be further improved (Refer Chapter 7, Fig. 7-6).

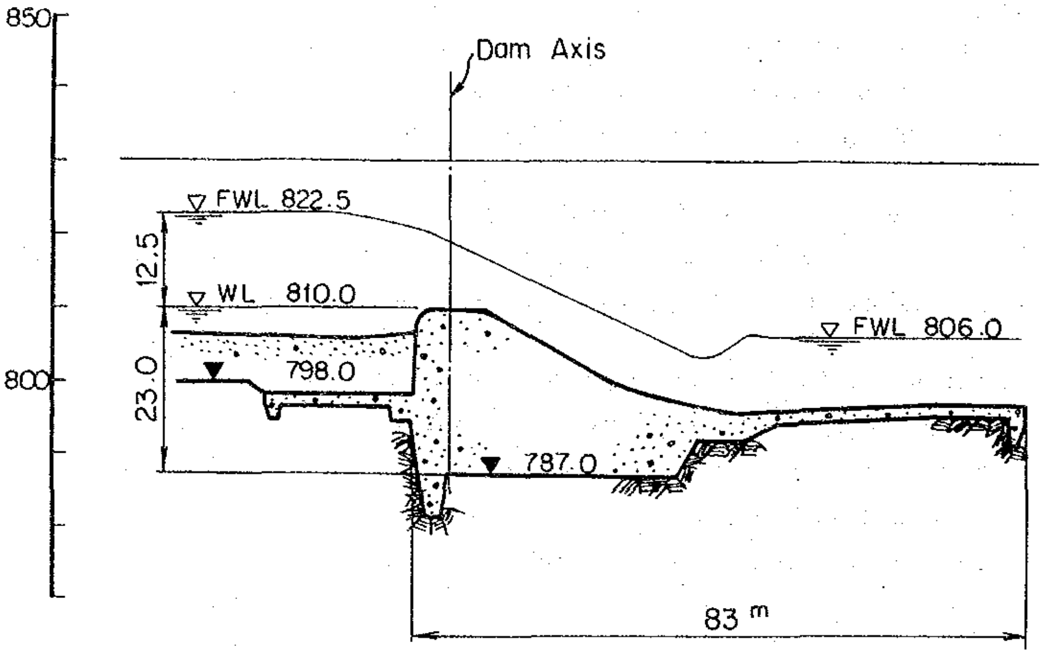
(iii) The creation of a buffer capacity by the adequate gate operation enable the reservoir to effectively cope with the debris flows and GLOF (Refer 5.7.5 Analysis of GLOF).

(iv) As the required regulating water depth is sharply reduced with the increase of the dam height, a rational gate design can be made (Refer 6.3.2 Required Effective Storage Capacity).

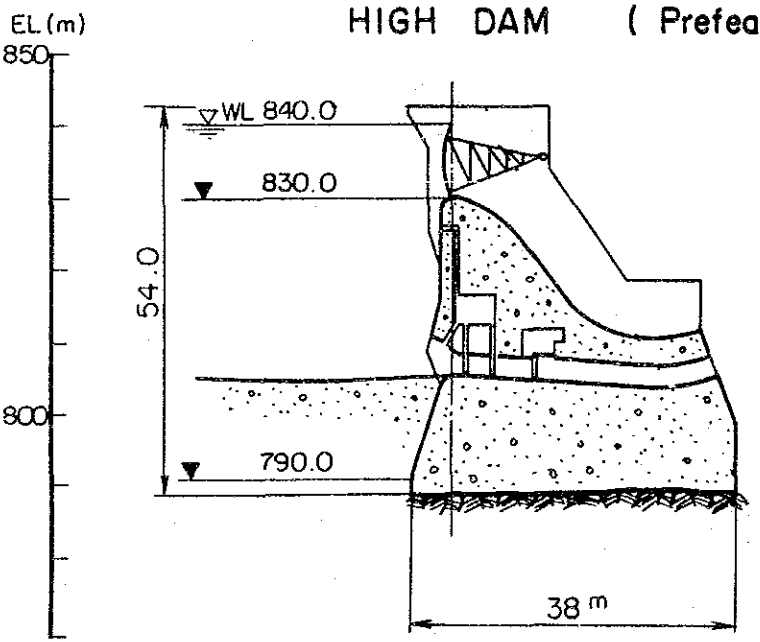
Gates provided at the dam crest will function as spillway gates and also sand flushing gates for maintaining of required regulating reservoir capacity. The most economical intake water level is to be selected on the basis of construction costs and benefits of the alternative schemes corresponding to various intake water levels.

Fig. 6–4 Typical Cross Section of Dam

LOW WEIR (Master Plan Study)



HIGH DAM (Prefeasibility Study)



6.3.2 Required Effective Storage Capacity

In planning the power development project purposed for daily regulation, the required effective reservoir capacity is defined as the one which enables peaking operation for the required peak duration time at the firm river discharge. As described in 7.2.2 of Chapter 7, the firm discharge and peak duration time are 87 m^3/s and 15 hours, respectively and the required effective storage capacity is then calculated to be $2.8 \times 10^6 m^3$.

As the gross storage capacity obtainable at this dam site is rather small and moreover, it will be completely filled with sand deposit within a short period, the effective capacity is to be created by installation of gates, hence, the required effective storage capacity will govern the dimensions of gate, intake and desanding basin. It is important to limit the effective storage capacity to its required minimum based on the study of actual operation pattern, in order to promote the economical situation of the project.

As to the daily load fluctuation in Nepal, two peak demands take places in the morning and evening, and the loads in daytime and nighttime decline as referred to Fig. 2-4 of Chapter 2. The trend above is considered to be further continued for some time and the Arun 3 power station will be operated in such a way as to take peak load in the morning and evening and base load in the other time.

Table 6-3 shows the operation pattern of this project in 2006 which is simulated on assumption that the daily load fluctuation at the said time will be about the same as that at present and also the Arun 3 power station will carry the peak load while the other plant the base load (refer to Fig. 6-5). This pattern is thought to be the most critical reservoir capacity for Arun 3 and the required reservoir capacity is estimated at $1 \times 10^6 m^3$.

For decision of the effective reservoir capacity of this project, it is also necessary to consider some other factors such as safe gate operation against abrupt increase of river discharge, additional regulating capacity needed for future development schemes upstream and downstream of the Arun 3 project, though it is difficult to estimate quantitatively the additional capacity so needed.

Based on the above consideration, it will be adequate to have the effective reservoir capacity of around $2 \times 10^6 m^3$ which satisfies that for forecasted operation pattern of this power plant as well as the other requirements. The effective drawdown corresponding to this reservoir capacity is 4.00 m as shown in Fig. 6-6 (reservoir capacity curve), taking the normal water level at EL. 840 m.

Fig. 6–5 Daily Peak Load Forecast and Ideal Arun 3 Operation Rule

(JAN. 2006)

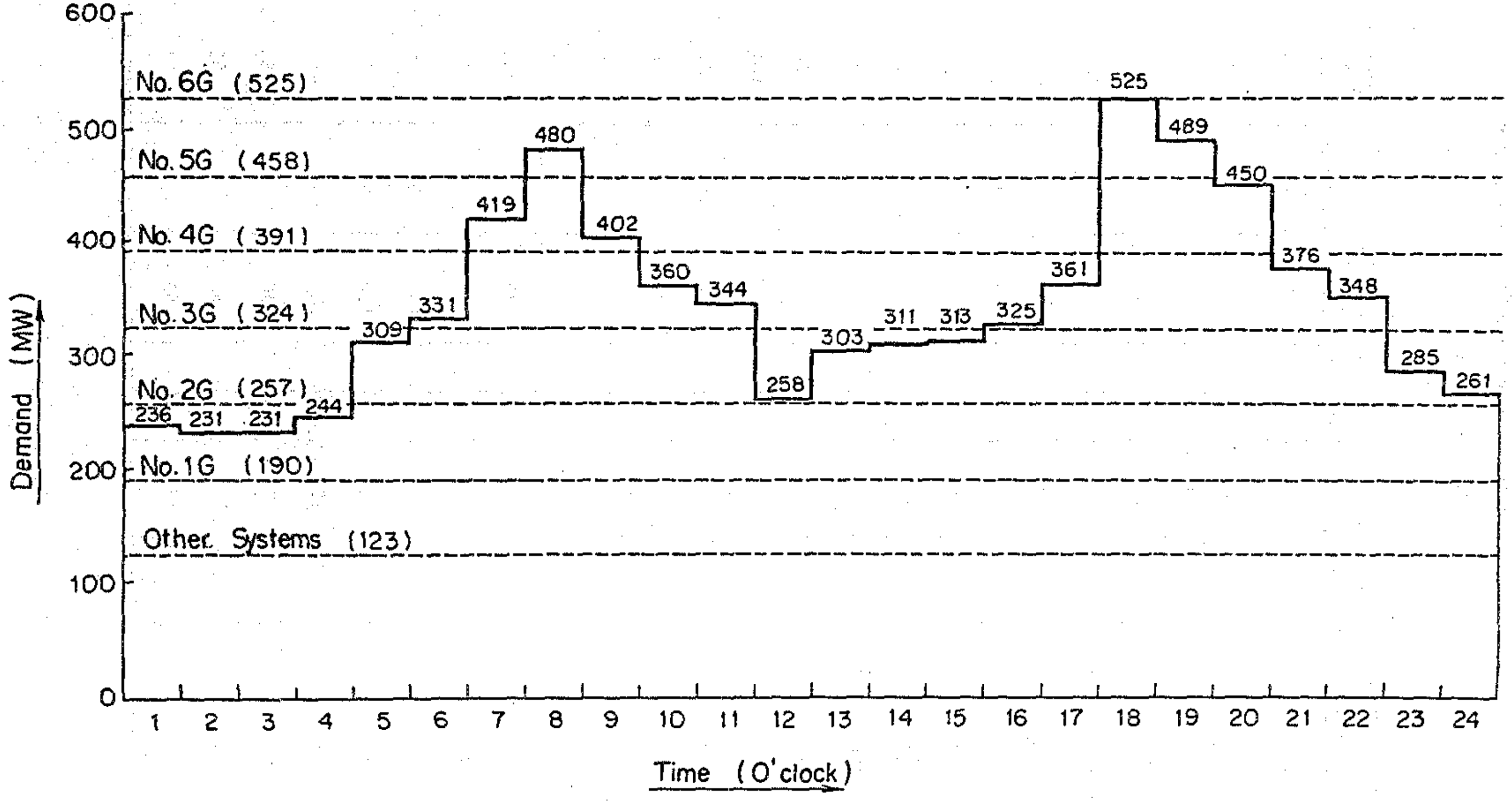


Table 6–3 Simulation of Hourly Operation in 2006

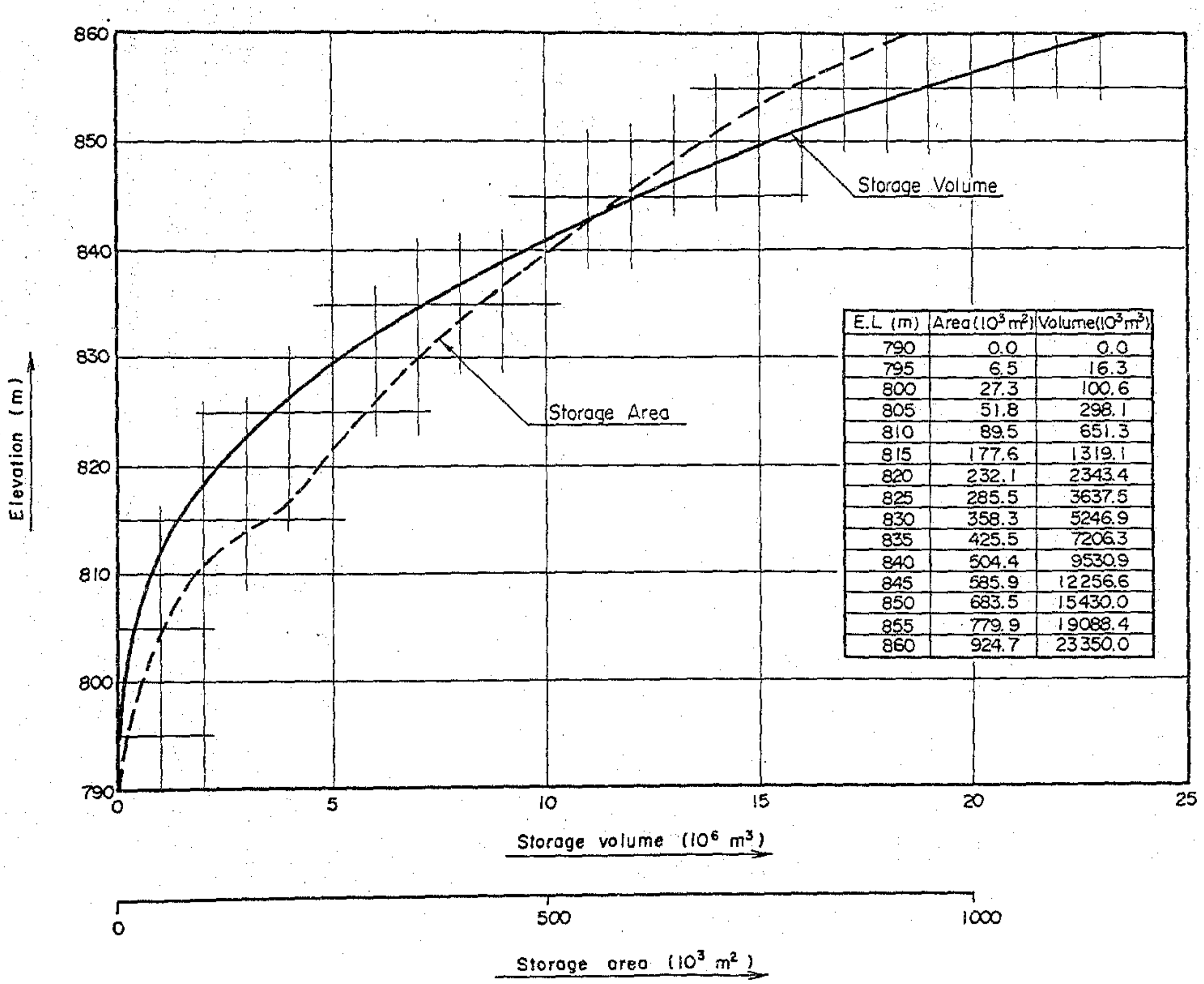
(Peak Daily Load = 525 MW)

Hour	Actual Load (MW)	Other Power System (MW)	Arun 3 (MW)	Inflow (m^3/s)	Outflow (m^3/s)	Deposit (m^3/s)	Summation (m^3/s)
1:00	236	123	113	87	45	42	42
2:00	231		108		43	44	86
3:00	231		108		43	44	130
4:00	244		121		48	39	169
5:00	309		186		74	13	182
6:00	331		208		83	4	186
7:00	419		296		118	-31	155
8:00	480		357		142	-55	100
9:00	402		279		111	-24	76
10:00	360		237		94	-7	69
11:00	344		221		88	-1	68
12:00	258		135		54	33	101
13:00	303		180		72	15	116
14:00	311		188		75	12	128
15:00	313		190		76	11	139
16:00	325		202		80	7	146
17:00	361		238		95	-8	438
18:00	525		402		160	-73	65
19:00	489		366		146	-59	6
20:00	450		327		130	-43	-37
21:00	376		253		101	-14	-51
22:00	348		225		90	-3	-54
23:00	285		162		64	23	-31
24:00	261		138		55	32	1

240

(864,000 m^3)

Fig. 6–6 Arun 3 Reservoir Storage Capacity



E.L. (m)	Area (10^3 m^2)	Volume (10^3 m^3)
790	0.0	0.0
795	6.5	16.3
800	27.3	100.6
805	51.8	298.1
810	89.5	651.3
815	177.6	1319.1
820	232.1	2343.4
825	285.5	3637.5
830	358.3	5246.9
835	425.5	7206.3
840	504.4	9530.9
845	585.9	12256.6
850	683.5	15430.0
855	779.9	19088.4
860	924.7	23350.0

6.4 Desanding Basin

In view of the topographical conditions at the upstream dam site, the first proposal will be the underground desanding basin on the left bank behind the dam. It is also technically possible to provide the desanding basin at the gently sloped alluvial deposit (EL. 820 to 810 m) on the left bank downstream of the junction of the Khoktak Khola and Num Khola with the Arun river.

As a result of geological investigations executed at the underground desanding basin site, no geological difficulties are found for construction of two caverns of each 20 m wide, 30 m high and 100 m long, when they are arranged apart from the folding zone existing upstream of the dam site, while giving adequate distance between them for safety.

As to the outdoor type desanding basin, a concrete structure of 50 m in width, 100 m in length and 20 m in height will be considered. With this structure, it is estimated that the bedrock elevation along the riverside wall will be at EL. 780 m or lower corresponding to the wall height of more than 60 m. Therefore, an outdoor-type desanding basin will involve more than 150,000 m^3 of concrete including foundation concrete and more than 300,000 m^3 of excavation, and its economic situation will be much poorer than that of underground type. Consequently, an underground type desanding basin is to be adopted for the succeeding studies.

6.5 Tunnel Layout

As to the layout of the waterway system including surge tank shown in the Prefeasibility Study, there are two alternatives, namely, a single-line system with one tunnel of 10 m in diameter and a double-line system with two tunnels of each 7.0 m in diameter. In the Prefeasibility Study, these alternatives were examined to estimate the economic feasibility of single stage or stagewise development of the Kaguwa project of 400 MW.

In addition to the advantage that the double-line system fits the stagewise development meeting the load demand forecast, it has the following superiorities.

(1) Provision of two tunnels will make possible to disperse damage from unforeseen troubles during generating operation, particularly, during the time from initial filling to the early stage of generating operation.

(2) Limiting the sizes of headrace tunnel and surge tank to medium scale, the better stability of the surrounding rock can be assured. Particularly, the stability of the excavated slope at the top of surge tanks in the vicinity of the powerhouse is of importance.

(3) In connection with tunnel driving, the countermeasures for unfavorable geological conditions which will be expected in excavation of long tunnel can be taken easily, when the diameter of excavated section is of medium size or smaller.

(4) The provision of two tunnels will shorten the overall construction schedule as the critical path may run through this activity.

Accordingly, it was decided to adopt a double-line system for the waterway from intake to powerhouse and two headrace tunnels with identical diameters are to be provided.

6.6 Powerhouse Site

Powerhouse sites which have been proposed are the Pikhuwa site and the Kaguwa site. Besides these two sites, the Solakhani site proposed in the Master Plan Study will also be studied just for reference. The locations of these sites including tunnel routes are as shown in Fig. 6-1 previously referred.

In addition to the field investigations such as seismic prospecting and core drilling previously performed, further investigations including seismic prospecting (2.69 km), core drilling (8 drill holes, 390 m) and topographic survey (1/500 scale, 383,000 m^2) were carried out at the Pikhuwa and Kaguwa sites in this Feasibility Study.

Based on the data collected from the field investigation and subsequent studies of the two sites, the following observations are made.

Pikhuwa Site

(1) With regard to the geological features at the Pikhuwa site, it can be expressed that massive and hard bedrock is distributed in general, with extremely thin overburden. The rock qualifications are from C_H to C_M class, while RQD is higher than 80% as a whole.

(2) Accordingly, the powerhouse of both outdoor and underground types can be constructed without any technical difficulties.

(3) Overburden at the proposed Pikhuwa surge tank site seems to be slightly thick and furthermore, a low-velocity zone ($Vp < 1.3$ km/s) is detected in the vicinity by seismic prospecting. However, at the portion from the middle to the bottom of surge tank and the upper horizontal portion of penstock, hard bedrock will be available.

(4) The depth of alluvial deposit distributed around the Pikhuwa powerhouse site is of 20 m to 25 m which is shallower than that at the Kaguwa site.

Kaguwa Site

(1) As to the Kaguwa site located immediately upstream of the confluence of the Kaguwa Khola with the Arun river and approxiamtely 1 km downstream of the Pikhuwa site, the topography is extremely irregular and foundation rock has been weathered to extremely deep part.

As a result of seismic prospecting (1.5 km), core drilling (4 drill holes, P-9, P-10, P-11, P-12, 200 m) and photogeological interpretations, erosion landforms are recognized over a considerably wide area (1.5 - 2 km^2).

(2) Overburden being the secondary deposits due to the above erosion thickly covers the area of the surge tank and the upper horizontal portion of penstock at the Kaguwa site as referred to drill hole P-9. It will be necessary to excavate this overburden and the underlying strongly weathered rock to EL. 780 m in order to obtain reliable rock foundation on which the structures can be constructed safely.

(3) Beneath the above rock formation, discontinuous low velocity zone and good rock foundation are alternately observed indicating complicated geologic structure. It is, therefore, considered not advantageous to construct the underground powerhouse at the Kaguwa site because of technical and economical difficulties that may be derived from uncertain and unknown factors.

(4) Between the midpoint of penstock and powerhouse site, sound foundation rock will be available under the medium thickness of overburden.

(5) Thickness of alluvial deposit around the powerhouse site will be around 30 m to 35 m which is thicker than that at the Pikhuwa site.

As observed above, the topographical and geological conditions at these two site are different and accordingly, economic analysis is made to clarify the relation between construction cost and benefit at these site. In the comparative study of these proposed powerhouse site, powerhouse of outdoor type which is applicable for both site is adopted. While, the increases in power and energy corresponding to the head difference of 15 m between the Pikhuwa and Kaguwa site are also taken into consideration.

The cost for civil works at the Kaguwa site will be 9.2% higher than that of the Pikhuwa site. The project cost of the Kaguwa site including electrical equipment costs and all others will be 5.6% over the Pikhuwa site as shown in Table 6-4.

On the other hand, the available head at the Kaguwa site is higher than that at the Pikhuwa site by 5%. Then, the sizes of benefit-cost ratios calculated for these two powerhouse sites are found to be on the same footing. However, the Kaguwa site has disadvantages such as (1) unreliability of geology around surge tanks which involves the potential of additional construction costs, (2) longer construction period for driving surge tank shafts and upper horizontal portion of penstock compared with the Pikhuwa site and (3) high possibility of unfavorable circumstances that may occur during construction operations, and accordingly, the Pikhuwa site is finally selected.

As to the type of powerhouse, both outdoor and underground types will be applicable at the Pikhuwa site as mentioned previously. As stated in Chapter 9, the cost for underground type powerhouse will be approx. 10% higher than that of outdoor type, however, the powerhouse of underground type is finally adopted as a part of the basic layout, since underground type powerhouse will be much safer than the other one in consideration of the topographical and hydrological conditions particular to the Arun river basin. The detailed economic comparison of the Pikhuwa and Kaguwa sites is as shown in 7.3.3.

Table 6–4 Main Features of Pikhuwa and Kaguwa Schemes

Item	Pikhuwa	Kaguwa
Main Dimension		
NWL (EL.m)	840	840
TWL (EL.m)	538	523
Gross Head (m)	300	315
Output (MW)	402.6	423.6
Tunnel DxL (m)	7.0x11,565x2	7.0x11,906x2
Surge Tank DxL (m)	14.00x70.0x2	14.00x92.5x2
Penstock DxL (m)	5.0-3.50x539x2	5.0-3.5x760x2
Construction Cost (10^3 US$)		
Civil Work	229,200	250,200
Project Cost	490,700	517,300

Note 1) Figures of tunnel length include those of power intake and desanding basin

2) Construction costs of civil work include those of hydraulic equipment