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臺灣水庫防淤之規劃及研究*

The Study and Planning of Reservoir Desilting in Taiwan

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摘　要

本文係參加去（73）年五月十二～十九日，在夏威夷東西中心舉辦「亞洲各國河川及水庫泥沙管理研討會」所提出之論文。介紹目前臺灣有關水庫防淤規劃、研究及實施之現況。其後經研討會主辦單位簡摘登載於國際水文季刊（Water International）1985年三月號。

臺灣位於西太平洋，面積約36,000 km²，呈狹長形，中央山脈縱走南北，有許多超過三千公尺的高山分布其間。因此一般河流均坡陡流短，許多更具有劇烈沖蝕性及嚴重之泥沙問題。亞熱帶氣候造成乾雨季節分明。除東北、北部外，其他地區一般五月至九月爲雨季，其餘月份爲旱季。尤其臺灣南部，約有70%之年雨量發生於六月至八月，15%降落於五月及九月，僅有15%分布於其他七個月內。

爲了調蓄豐水季大量餘水以供旱季使用，臺灣已建造27座水庫，5座正在施工中，而某些則正在積極的規劃。如於南部某些河流興建水庫，因爲泥沙問題嚴重，水庫完成後，其可用壽命短促，延長使用時間之可行方法爲空庫定期以排沙閘門排沙。雖然這種方式一直仍在不斷的研究及改進中，但某些實例執行確實有效。本文將介紹一座規劃中的水庫，如何採用特殊水庫運用方式防淤，併將所擬基本設計步驟加以報告，願拋磚引玉，以求改進。

Abstract

Taiwan is an island located in the western Pacific Ocean, about 36000 km² in size. It has a banana shape with high mountains running roughly in the north-south direction with many peaks exceeding 3000 m in elevation. Consequently, the streams on the island are generally short and steep, many with high sediment loads. The climate is semitropical, with high precipitation between May and September and relatively dry during the rest of the year. In southern Taiwan nearly 70% of the annual rainfall occurs in the period of June through August, another 15% in the months of May and September.

In order to store the large amount of runoff water in the wet summer season for later use, 27 reservoirs have been constructed, some are under

* 本文轉載自"Water International", March, 1985. 經作者同意載轉，謹致謝忱。（編者啓）

construction and several are being planned. For streams having a heavy sediment load such as those in southern Taiwan, the reservoir will be silted in a short time. One possible approach to prolong the useful life of the reservoir is to flush the sediment in the reservoir periodically by using sluice valves. Although the scheme is still under study, some tryouts have been implemented effectively. The proposed dam-reservoir project that adopts a special scheme will be presented in conjunction with the basic design procedures.

Introduction

Taiwan is oblong in shape, about 377 km long from north to south and 142 km wide at the widest section, and about 36000 km^2 in area. Less than one third of this area is suitable for cultivated agricultural uses, another two thirds is mountainous area. The high mountains, running roughly in the north–south direction, with many peaks exceeding 3000 m in elevation, become the central ridge of the island. Consequently, the streams on the island are generally short and steep, many with a heavy sediment load owing to the topographical conditions, intense rainfall and erosive geologic characteristics of the watershed area.

Since the annual ranifall is 70% concentrated in the period of June to August, the other months are relatively dry. Figure 1 indicates the annual precipitation and its fate and incorporates the water uses at present and as predicted for the year of 2001.[1]

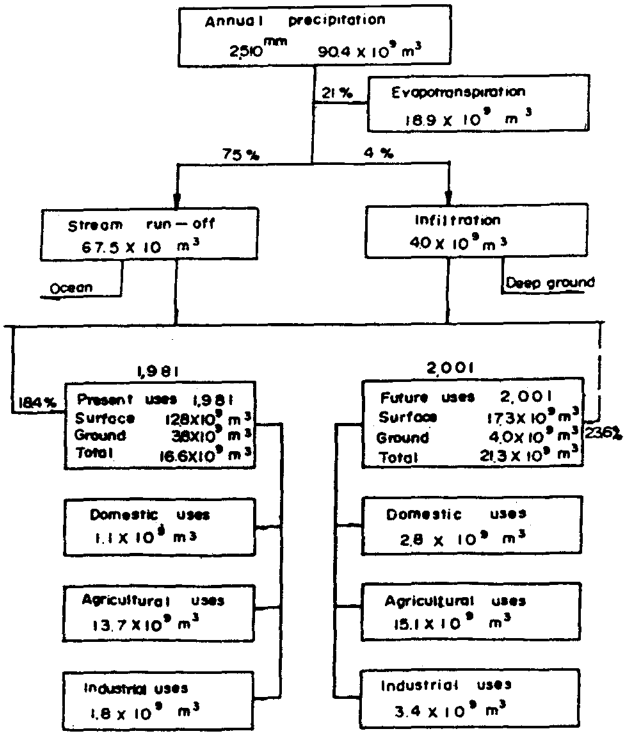

Figure 1. Schematics of water resources in Taiwan.

In the conventional approach a reservoir and dam is designed, taking into consideration the silting of the reservoir from retention of the sediment-laden inflow. For streams having a heavy sediment load such as those in Taiwan, the reservoir will be silted in a short time.[2]

In this paper, the sedimentation of existing reservoirs will be introduced first, then an explanation of reservoir desilting practice in Taiwan.

Climate of Taiwan

Since the Tropic of Cancer passes through the middle south of Taiwan, its climate is semi-tropical with high precipitation between May and September. It is relatively dry during the rest of the year, except in the north near Taipei, where light but persistent rainfalls also occur in November through February. In southern Taiwan nearly 70% of the annual rainfall occurs in the period of June through August, another 15% in the months of May and September, and another 15% in the rest of the year.[2]

The average annual precipitation is 2510 mm, which is abundant, though very unevenly distributed. During the wet season, intense rainfall occurs and results in serious watershed erosion. A great deal of heavily sediment-laden flow is concentrated in a short time and empties itself into the ocean rapidly during the dry season, when, except for several larger rivers, almost all of the streams in Taiwan are nearly dry. At present water shortages occur frequently during the dry season. The basic pattern of water resources utilization is formulated to use the run-of-the-river water first, then to construct reservoirs to store the abundant water during the wet season for later use. The problem is the heavy sedimentation in the reservoir induced by serious watershed erosion. The distribution of the annual rainfall of southern Taiwan is shown in Figure. 2.

Reservoir Sedimentation in Taiwan

There are 27 existing reservoirs in Taiwan, some for a single purpose and others for multiple purposes. Data concerning sedimentation for 12 of these reservoirs are given in Table 1. Information for the other 15 reservoirs is not included for various reasons, including insufficient data, short records, and off-stream hydropower reservoirs with little silting. The reservoirs in Table 1 are listed according to their locations from north to south of Taiwan and all are in the western foothills geological region of the island. The first six are located in the north and the last six are in the south.[2]

Compared to reservoirs in the United States, the silting problem in Taiwan reservoirs is much more serious, especially in southwestern Taiwan. The geological formation in this region is Cainozoic mudstone, a very erosive rock. The region's annual precipitation varies from 1500 mm on the west coast to 3000 mm

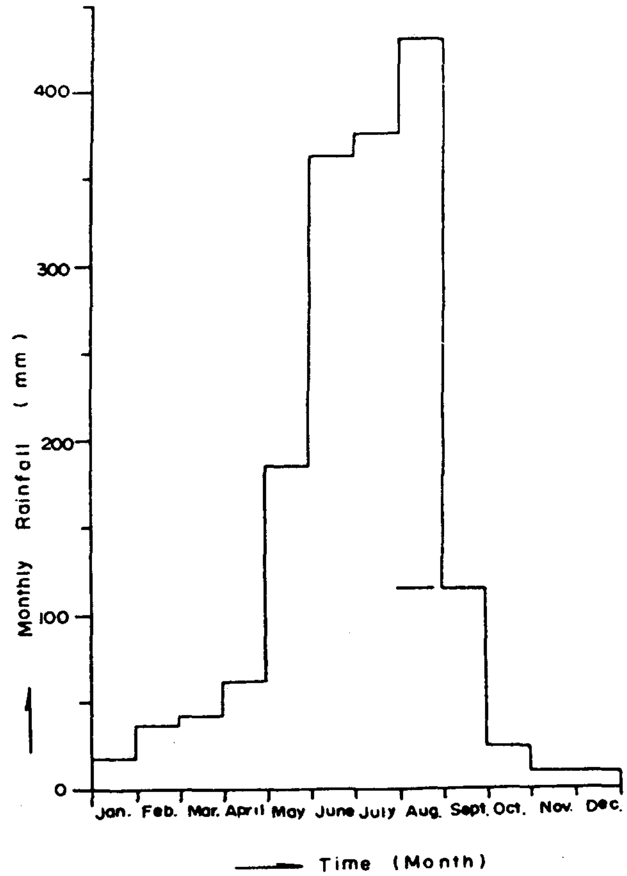

Fig. 2 Rainfall in southern Taiwan

Table 1. Storage depletion and probable life of reservoirs in Taiwan

Reservoir	Drainage area (km^2)	Initial storage capacity (10^3 m^3)	Period of record (yrs)	Storage depletion (10^3 m^3)	Average annual sediment accumulation (10^3 m^3)	Average annual depth eroded from drainage area (mm)	Average annual storage depletion of initial capacity. (%)	Probable reservoir life (yrs)
Si-su	6.48	580	45	149	3.31	0.51	0.57	175
Su-men	763.40	315960	20	44580	2175.00	2.85	0.69	140
Ta-pu	100.00	90000	19	4770	251.05	2.51	2.79	40
Chingzauhu	30.30	1100	22	850	38.64	1.28	3.51	30
Min-te	61.08	17700	5	2207	441.40	7.23	2.49	40
Te-chi	592.00	256000	2	2777	1388.50	2.35	0.54	185
Lu-laochie	7.50	3780	37	2310	62.43	8.32	1.65	60
Tzen-wen[2]	496.00	712700	9	43114	4422.00	8.92	0.62	160
Pai-ho[2]	26.55	27417	15	8627	575.13	21.66	2.10	50
Jensanpei [2]	10.60	7000	18	4260[3]	236.67	22.36	3.58	30
Wusantou[1,2]	60.60	156236	34	35586	1046.65	17.28	0.67	150
Akungtein[2]	31.87	18000	28	14200	507.14	15.91	2.82	35

[1] Wusantou is located downstream of Tzenwen. The total drainage area of Wusantou including Tzenwen is 556 km^2

[2] The last five reservoirs in the Table are located in the Cainozoic mudstone area.

[3] Jensanpei Reservoir maintains a constant capacity because of efficient de-silting through flow control.

in the central mountain region. Due to the climatic conditions (high temperature and high precipitation) and the geological conditions of soft and erosive rocks, the erosion rate in southwestern Taiwan is very high. The average annual sediment accumulation rate of reservoirs in this region converted into depth over the drainage area ranges from 9 mm to 22 mm. As shown in Table 1, the sedimentation rate is about three times the heaviest rate in the Yellow River basin[4] and ten times higher than that of reservoirs in the United States.[5]

The erosive condition in northern Taiwan is much better than that of the southwest because of the climate and geological conditions. The precipitation in the north is distributed more evenly during the year than in the south, and the geological formation is mostly sandstone. The average annual sediment accumulation rate for reservoirs in northern Taiwan ranges from 0.51 mm to 7.23 mm, about one half of that of the south.

The probable life of a reservoir depends not only on the erosion rate, but also on the reservoir storage capacity. The larger the capacity the longer the life. The probable life of the reservoirs in Taiwan ranges from 30 years to 185 years as shown in Table 1.

Reservoir Desilting Practice in Taiwan

Except on certain small reservoirs for municipal or industrial purposes, it is generally impracticable to remove any substantial quantity of silt from the reservoir after it has been deposited. There is a reservoir, Su-Men Reservoir, located about 60 km from Taipei where we have tried to remove the deposited silt by dredging. Every year 300000 m^3 of deposited sediment will be removed, but, because that is only 13% of the average annual deposition, it might not be effective enough. The most practical remedy lies in preventing permanent deposits. Under certain circumstances, this is possible.

At the Jensanpei Reservoir we dealt with the silting problem by adopting the Spanish method[2,6]. The Jensanpei Reservoir was built in 1938, for the purpose of industrial water supply. The owner of the reservoir is Taiwan Sugar Company. In an 18-year period from 1938 to 1955, the storage depletion due to silting was 4260000 m^3. The reservoir flushing project was recommended by Professor C. Jing[7] of National Taiwan University in 1955. A Flushing gallery was built through the base of the dam with a horizontal tunnel of 1.5 m diameter and a vertical tower of the same size. Flushing for desilting is arranged by emptying the reservoir between May and July and permitting natural floods to flow through. Since the harvest period of sugar cane is between November and the following April, sugar mills do not use any water between May and October. The reservoir operation pattern is shown as Figure 3.

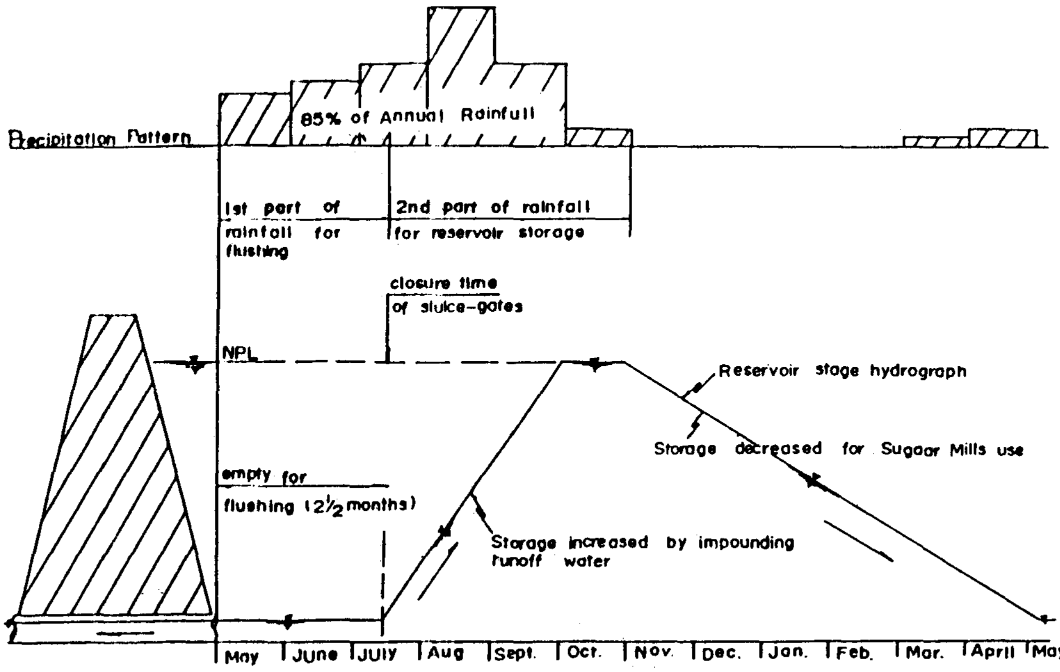

Figure 3. Operation pattern of Jensanpei Reservoir.

The efficiency of the flushing in Jensanpei Reservoir is perfect. In the 25 years since the flushing operation started in 1955, the storage capacity of the reservoir has remained almost constant. The average annual silting rate was 237000 m^3 during the period of 1938 through 1955. For the 25 years from 1955 to 1979 the average annual silting rate was only 1200 m^3. The storage depletion curve of the reservoir is shown in Figure 4.[2]

In 1983, Professor C. M. Wu studied the relationship between flushing flow and desilting efficiency. He found out that the desilting sediment content, C_v, can be calculated on the basis of the following regression equation:

$$\ln C_v = 0.578 + 0.019 \ln \frac{V}{W} S + 0.041 \ln \frac{Vh}{\nu} \quad (1)$$

in which C_v is the content of desilting sediment by volume expressed as a percentage,

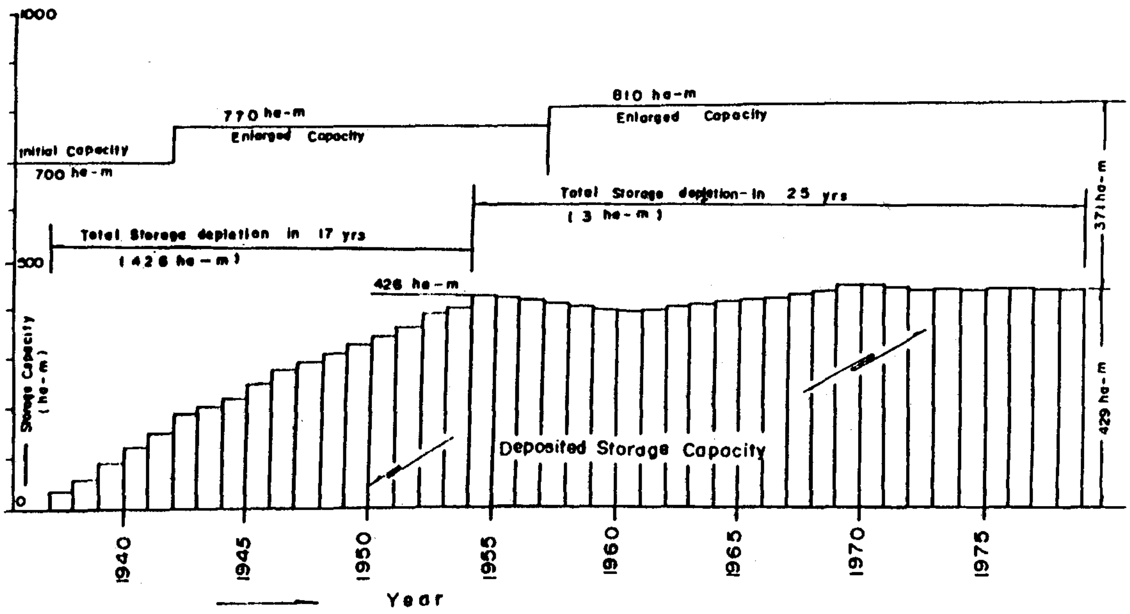

Figure 4. Storage capacity depletion of Jensanpei Reservoir.

V is the flow velocity in the gallery, S is the energy slope of the desilting gallery, h is the depth of the flow in the gallery, W is the fall velocity of the silt particles, ν is the kinematic viscosity of the water. In dimensionless factor $(V/W)S$, VS represents the rate of energy consumed during the desilting operation, and Vh/ν is the Reynolds number of th flow. This equation, though, is rather simple in terms of the complicated factors involved, yet it is expressed in dimensionless terms. Hence can be used to predict future desilting quantities and can be extented to predict the efficiency of desilting galleries for other reservoirs.[6]

Reservoir Desilting Scheme of the Proposed Ho-Ku Reservoir

The Ho-Ku Reservoir is a proposed reservoir, located upstream of Ho-Ku Creek, for the purposes of providing municipal and industrial water supply to the southern region of Taiwan. It also has a seriously erosive watershed. Therefore, a reservoir desilting scheme, a modification of the Jensanpei desilting pattern, was suggested as the operating pattern for the proposed Ho-Ku Reservoir to prolong its probable life. It is still under planning and study.

Before a reservoir desilting scheme is arranged and required to be effective, a water utilization pattern should be conceived and formulated first, because the reservoir desilting scheme is only effective under certain circumstances. According to the desilting experience of Jensanpei Reservoir an empty period has to be arranged during the flood season for at least two months, about a half of the entire wet season. Consequently, the water storage for later use in the current year will often not be enough. In the Jensanpei case, supplemental water is pumped from a downstream creek during periods of drought.

Figure 5 shows the available run-of-the-river water for the downstream reach of the

Kaopin River. The water is abundant during the wet season from June through November, in other months the water flow is relatively small.

The increasing water demand for the progress of economic development of the southern region of Taiwan; especially for the Great Kaohsiung District, will reach approximately 25 m^3/s or 2.16 x 10^6 m^3/day, by the year 2001. Table 2 is the analysis of the water demand, water supply,and the water shortage which will have to be supplemented by the Ho-Ku Reservoir.

Based on Table 2, a empty period for the Ho-Ku Reservoir can be arranged between June and September for sediment desilting, the exact period is formulated using sediment routing, a sequential routing through Ho-Ku Reservoir using 21 years, 1959–1980, of hydrological data.

The Ho-Ku Reservoir is divided into two bays, the forebay will function as a settling basin. The water

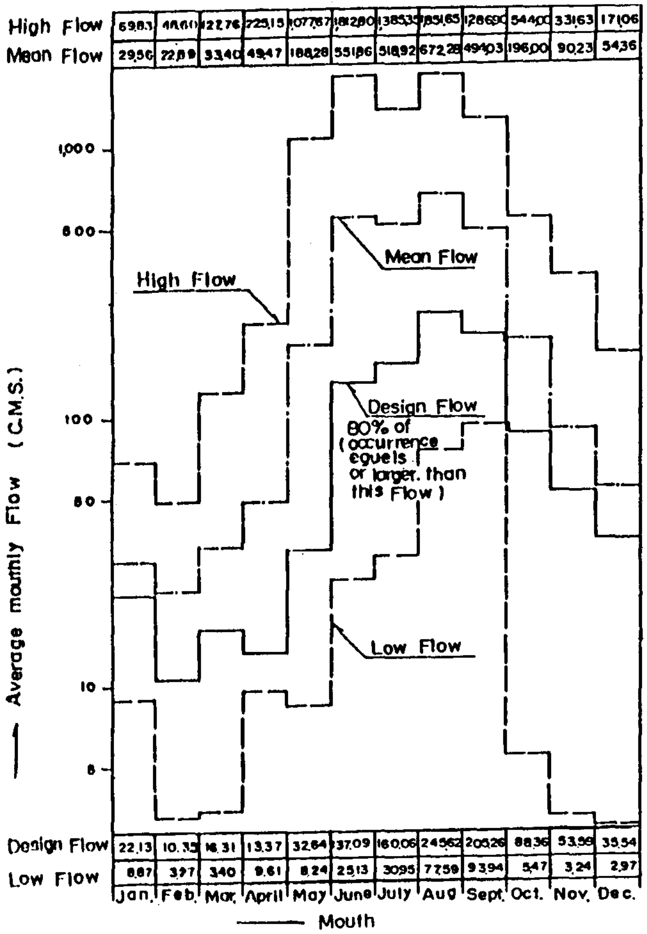

Figure 5. Available water of the Kaopin River (1940–1982).

Table 2. Water supply pattern of Great Kaohsiung District (units m^3 x 10^4)

	Jan.	Feb.	Mar.	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Total
Demanded water (2001)	6696	6048	6696	6480	6696	6480	6696	6696	6480	6696	6480	6696	78840
Available water (80%)	6136	4599	5207	5315	6424	6480	6696	6696	6480	6612	6222	6431	73298
Supplemental water (Ho-Ku Reservoir)	560	1449	489	1165	272	0	0	0	0	84	258	265	5542

will flow into the forebay for sedimentation then over flow into the afterbay for storage. The sediment carried by inflowing water will nearly all be deposited in the forebay for periodic flushing. There is flushing tunnel of 5.5 m diameter and length 1500 m. It is designed to be erected at the low point of the forebay, based on the flow routing and flushing efficiency prediction. The major design procedures are formulated as follows:

1. The trap efficiency of the forebay can be estimated based on Churchill's curve, Brune's curve or by using the Einstein equation.[9,10]

2. The representative flows through the reservoir are selected from the duration curve of the river at the Ho-Ku damsite.

3. Flow conditions for the representative flows that flow through the reservoir are routed using historical records.

4. After flow rounting, the flushing efficiency can be estimated by using Eq. (1) to decide the operation pattern for the Ho-Ku Reservoir.

The water utilization pattern in the southern region of Taiwan during the year of 2001 is indicated not only in Table 2, but can also be shown as the set of systematic schematics of Figure 6. Figure 7 shows the general layout of the Ho-Ku Reservoir.

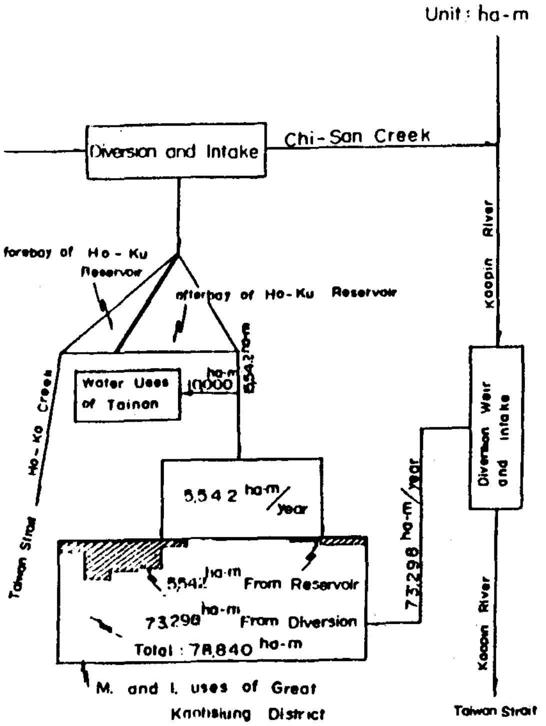

Figure 6. Schematics of water supply pattern of the Great Kaohsiung District.

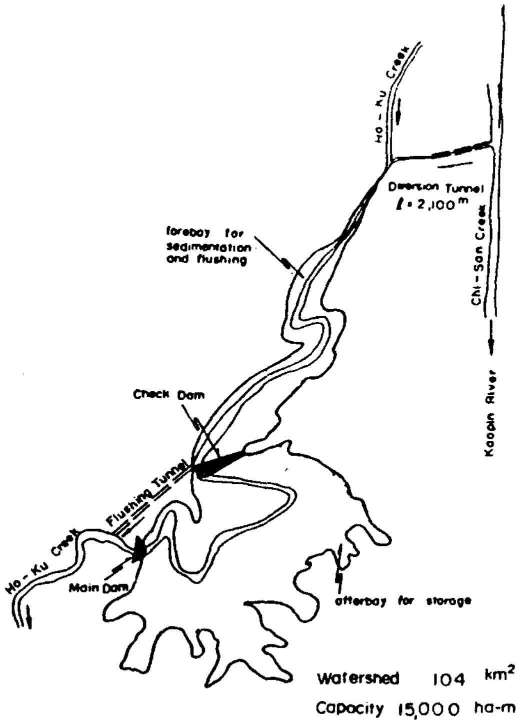

Figure 7. Schematics of the general layout of Ho-Ku Reservoir.

Conclusions

As described previously, the reservoir sedimentation rate in southern Taiwan is very high; Without any special scheme to deal with the sediment, a reservoir in this area will be silted in a short time and the project will be infeasible economically.

The special water utilization pattern and reservoir sediment control scheme which are conceived for the southern region of Taiwan and the Ho-Ku Reservoir are first to use the available run-of-the-river water, then arrange an empty period for the Ho-Ku Reservoir to sluice the turbid water during the flood season and store clean water. This is mostly diverted from the upstream reaches of the Kaopin River at the end of the flood season for the supplementary uses of the region, from October through the following May.

According to the flow routing, trap efficiency computation and flushing efficiency estimation, the forebay of Ho-Ku Reservoir will function as a settling basin and will contain almost no permanent deposition. The probable life of the afterbay of Ho-Ku Reservoir would be problonged from 70 yeras without any desilting scheme to 470 years with the special operation pattern.

Although the Ho-Ku Reservoir is till being planned, it has been decided to develop it according to the desilting scheme and water utilization pattern starting in 1986. In order to assure the flushing efficiency of the Ho-Ku Reservoir, it was suggested that a hydraulic model experiment be carried out to compare the results of the test with the mathematical computations.

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