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CONTENTS

I. Introduction

Irrigation systems for rice double cropping culture in the tropical monsoon area of Southeast Asia are characterized by a large scale but a low level of facilities. As the tropical monsoon climate has a distinct dry season, the irrigation systems are composed of a huge reservoir as water source for the dry season, long head race and canals, and large-scale terminal irrigation blocks in which plot-to-plot irrigation prevails. It seems that a series of construction of major irrigation projects with high potential for rice double cropping has almost been completed in the tropical monsoon area. However, rice double cropping does not appear to have been easily achieved as originally planned in the completed projects mainly due to the imbalance between water demand and supply. The main factors underlying the water problems can be listed as follows:-

1) overestimation of available water supply, due to lack of hydrological and meteorological data.
2) underestimation of water requirement.
3) insufficient terminal facilities (low canal density).
4) insufficient management of irrigation systems and wasteful water use by farmers.

In addition to the above, the following factors also cannot be overlooked.

1. The deliberate estimations of water requirement and available water supply in the design of a project so as to expand the benefited area as much as possible and to increase the cost benefit ratio for the project as much as possible.

2. The application of upland irrigation methods to paddy field irrigation, resulting in the supply of a quantity of water below the field capacity to minimize the percolation and seepage losses. Factor 4) is due to insufficient information about the management of irrigation systems based on time series analyses of water flow in canals and paddy fields.

The purpose of this study is to analyze the hydraulic and hydrological problems related to the management of irrigation systems, which are built on a large scale but with a low level of facilities, as well as to identify the factors which bring about the difference between designed and actual conditions in the water balance based on on-site experiments carried out in the tropical monsoon area. In this study, the Muda Irrigation Scheme of Malaysia and the dry zone area of Sri Lanka were selected as case study areas.

In Malaysia, since irrigated rice cropping culture is a comparatively recent phenomenon in agricultural history, only few studies on management of irrigation systems are available. Only a limited number of achievements have been made both from the political and socio-economic aspects and engineering aspect. Greater efforts should be made to further promote studies on management of irrigation systems from various points of view.

In the dry zone area of Sri Lanka, a large number of studies on management of irrigation systems have been carried out continuously. However, emphasis appears to have been placed on studies based on political and socio-economic aspects compared with the engineering aspect. Seventy percent of all the academic achievements on the management of irrigation systems are based on the former. Even out of the thirty percent categorized as the latter, many achievements have political and socio-economic tones. Therefore, for further studies on management of irrigation systems, greater efforts should be concentrated on the engineering aspect.

Especially, time series have not been considered sufficiently for the studies on management of irrigation systems in and around the two case study areas.

Irrigation systems can be divided into three parts, i.e. irrigation area, reservoir (water source), and conveyance and distribution system. Water management in an irrigation system with a reservoir should be functioning effectively from the water source to the terminal lots. The irrigation system ought to be operated so as to distribute timely the required irrigation water to the fields. Water saving attempt at the terminal level should contribute to the reduction of the dependence on reservoir water. Management of the conveyance and distribution system has a significant meaning in connecting the supply and demand organically. The time lag of flow travelling in the irrigation systems which is an important factor determining the loss of irrigation water in the systems themselves ought to be kept in mind all the time for the operation of the facilities in the systems.

In this paper, several aspects which ought to be considered for improving the management of irrigation systems with reservoirs are discussed from the engineering point of view. The paper is organized in seven chapters including this chapter.

In Chapter II, the studies on the management of irrigation systems in Malaysia and Sri Lanka are reviewed.

In Chapter III, the natural environment, the current conditions of rice double cropping and management of irrigation systems in the study areas are examined.

In Chapter IV, the components of water management in the irrigation area are discussed. The mechanism of water consumption and water requirement in terminal paddy fields is analyzed based on the data observed in the study areas of the two countries.

Chapter V analyzes the components of water management in reservoir. In Section one, the characteristics of reservoir inflow (runoff) from the catchment covered by tropical forests are examined by time-series analyses. Section two provides a description on the management of water release from the reservoir and proposes a reservoir operation rule. All the studies in this chapter were carried out based on the data observed in the Muda Scheme.

In Chapter VI, the management of conveyance and distribution systems is discussed. Section one focuses on the conveyance and distribution losses. In Section two, a case study on flow-arrival time in long canal systems is analyzed based on the actual flow data obtained in the Muda Scheme. Section three studies the problems and measures required to improve the management of the distribution system.

Finally, in Chapter VII, the main findings in the paper are summarized and conclusions are drawn.

II. Review of the studies on the management of irrigation systems in Malaysia and Sri Lanka

1. Malaysia

In Malaysia, irrigated rice cultivation is a comparatively recent phenomenon in agricultural history. Rainfed single cropping had prevailed until about 1965. Since then, large investments have been made to extend and improve the irrigation infrastructure for rice double cropping through a series of five-year national plans. Presently there are eight major irrigation areas under double cropping including the Muda and Kemubu irrigation schemes, popularly known as the granary areas in Malaysia.

There are few studies on the management of irrigation systems in Malaysia. Only a limited number of publications are available on the political and socio-economic aspects as well as the engineering aspects of irrigation management. On the political and socio-economic aspects, publications include those of D.C. Taylor [1979, 1980, 1981, 1985], C. Bell et al. [1982], G. Kalshoven et al. [1984], D. E. Short and J.C. Jackson [1971, 1972], R. Rohizad [1980] and C.C. Lim [1985].

D.C. Taylor carried out an economic analysis on irrigation development and management of irrigation systems in Malaysia. In his studies on costs and performance of irrigation systems of different sizes, types, and locations in Malaysia, he drew the following conclusions [1981, 1985] :-

i) Larger irrigation systems in Malaysia bring about somewhat higher yields and greater annual cropping intensities than smaller systems.

ii) Smaller gravity systems may be less costly to build and operate than larger ones.

iii) Among the irrigation types, pump systems are more costly, followed by gravity diversion systems and controlled drainage systems.

iv) Irrigation costs are highest in East Malaysia and lowest on the east coast of Peninsular Malaysia, where yield levels and annual cropping intensities are also among the lowest.

v) Suitability of a particular type or size of system in a given location is strongly conditioned by physical factors.

He carried out an economic analysis of irrigation scheduling for the Kemubu scheme, drew his conclusions as follows [1985] :-

i) Farmers in the Kemubu scheme complete rice cultivation operations substantially later than the dates called for in the irrigation schedule.

ii) Factors associated with farmers' failure to follow the schedule include delay in the first supply of water to their fields, late availability of tractors for preparing the land, and delayed harvest of the previous crop.

iii) Farmers who do not follow the schedule have lower mean rice yields than those who do because they frequently have to harvest under flooded conditions, and because of greater pest damage.

C. Bell et al. analyzed in detail the economic impact of the Muda irrigation project on the surrounding regions as well as on the project area [1982]. They analyzed the project's direct and indirect effects and also carried out a social cost-benefit analysis. Using the numerical models constructed through a series of analyses, they predicted the changes in the region that were likely to occur over the next decade or so and determined how public policy might influence the course of events.

G. Kalshoven et al. implemented an interdisciplinary field research program in an irrigated paddy farming area within the Kemubu scheme [1984]. Their findings were as follows:-

i) The construction of a large irrigation scheme and the introduction of double cropping brought about many changes in the farm economy.

ii) Topographic conditions and inadequate distribution of water resulted in wastage during normal weather and in scarcity during dry periods.

iii) Poor performance of the irrigation systems was attributed to flaws in the design and to deficiencies in management, including supply of water to the irrigation units and use by the farmers within the units.

iv) In their uncertainty about supply, farmers look for individual solutions, including blockage of quaternary channels, and are not motivated to take collective action to cope with distribution problems.

They recommended the following as possible ways in which the authority carrying out the management of irrigation systems could improve irrigated paddy farming in the scheme:-

i) To extend and improve existing field ditches,

ii) To regulate discharges to the irrigation units for an even and effective distribution,

iii) To increase the capacity of the main drain and to maintain its capacity by regular clearing of weeds, and

iv) To develop procedures and control measures that guarantee a more equitable sharing of water within the units.

Regarding the engineering aspects, the main achievements include those of S.H. Thavaraj [1975, 1978], G.A.W. Van de Goor and G. Zijlstra [1968], L.H. Pang [1978], T. Terasart [1983] and S. Yashima [1986].

S.H. Thavaraj developed a theoretical method for estimating the presaturation requirement of the paddy fields [1975]. His proposal was highly appraised and has been adopted for the planning of irrigation projects. However, some modifications seem to be required for the precise estimation of presaturation requirement.

G.A.W. Van de Goor and G. Zijlstra analyzed the irrigation requirements for double cropping of rice based on on-site experiments carried out in five selected areas [1968].

L.H. Pang reported on the advantages of fiberglass-reinforced polyester (FRP) flumes for use for tertiary channels [1978]. FRP flumes have recently been developed in Malaysia to carry water above ground and are being introduced in some of the irrigation projects. FRP flumes can be installed more rapidly than conventional earth channels, thus precluding crop loss in a season. They require less right-of-way acquisition, less maintenance, and enable to save irrigation water. The agricultural and engineering benefits that accrue from the FRP flumes more than compensate for their high capital costs.

T. Terasart carried out a study on water management in the Besut irrigation scheme under the UNDP water management pilot scheme [1983].

S. Yashima analyzed the water balance, irrigation efficiency and soil bearing capacity in low and flat paddy land for a canal density of 10m/ha based on on-site experiments [1986].

Greater efforts are yet required in Malaysia in studying the management of irrigation systems from various aspects including crop diversification.

2. Sri Lanka

In the dry zone area of Sri Lanka, due to the effective water usage based on reservoir (tank) systems, irrigated rice cultivation was highly developed from the third century B.C. till the twelfth century A.D.. The studies on the management of irrigation systems in Sri Lanka started with the evaluation of these ancient irrigation works.

Several studies deal with the ancient irrigation systems of Sri Lanka including those of H. Parker [1909], R.L. Brohier [1934, 1941], C.W. Nicholas [1959], S. Arumugam [1969] and R.A.L.H. Gunawardana [1971]. At least from the fourth century B.C. onwards, small village tanks were built resulting in a social system based on a "one tank - one village" concept [Siriweera 1982]. A large number of these ancient village irrigation works were constructed with communal labour and were the collective property of the villagers [Paranavitana 1958]. Routine maintenance of the village tanks was taken care of by the villagers themselves, while major repairs were entrusted to specialized groups of hired Tamil labourers [Abeyratne 1986]. From around the first century A.D., larger reservoirs began to be constructed across non-perennial rivers as the large-scale state enterprises. Subsequently, some of these were enlarged and expanded. Stone anicuts (weir) were built across even perennial rivers so as to divert water by means of canals to these tanks. By the end of the fifth century, the two well-known complexes of irrigation works— one drawing on the Mahaweli River and its tributaries, and the other on the waters of the Malwatu Oya and the Kala Oya— had been formed. In the subsequent centuries these two main hydraulic complexes were further developed, and they reached their last and most important stage of development during the reign of Parakramabahu I in the twelfth century [Siriweera 1982].

A. Abeysinghe [1978] pointed out several interesting features in the ancient storage irrigation systems as follows:-

i) The elevations of outlets of storage reservoirs were well fixed so as to command the land most suitable for paddy.

ii) The spill water was not directly discharged into the stream below, but a part of it was led through a canal to feed another feeder tank.

iii) Water was diverted from perennial streams into storage reservoirs on the basis of the "trans-basin canal" concept, the capacity of which could not be fully utilised by the runoff from their own catchments.

iv) All the large reservoirs built by the ancient Sinhalese were earth embankments thrown across non-perennial streams.

v) Water conservation was promoted in a series of village tanks where the fields under the highest tank in the valley would extend up to the periphery of the water surface of the next lower tank in the valley by which the drainage water of the higher tract would accrue to the next tank in the valley.

In addition to the above-mentioned features, H. Nakamura [1986] and T. Kimura [1978] observed the following technical characteristics of the storage irrigation systems in the dry zone:-

i) Sluices and "bisokotuwa"

The sluices are made of dressed stone slabs on the innermost (water) side reinforced by several layers of brick masonry on all 4 sides, which in turn is supported by a layer of carefully selected compacted clay. This system ensures that leakage of water through the sluice into the earth embankment is kept down to an absolute minimum. The cross-section of the sluice barrel increases from the beginning on the reservoir side, to the end on the downstream side. As the increase in area is about 7 times, velocity of the water is reduced in the course of its passage through the barrels so as to minimize the damage to downstream channel at its outlet. Access to the horizontal sluice barrel is through a vertical shaft referred to as "bisokotuwa" which is also made of stone and reinforced with brick and clay. The "bisokotuwa" is now called a "valve-pit" in modern sluices [The People's Bank 1977, Gunawardana 1978].

ii) A large earth dam is built with low height but long length so as to ensure safety against possible collapse.

iii) "Level-crossing canal" is facilitated in order to distribute water among the cluster of reservoirs.

iv) Detailed surveys were carried out for very precise construction of irrigation systems.

v) Rational reservoir management was carried out including especially effective usage of desilted mud from the reservoir bed for soil dressing in the command area as well as for the reinforcement of the earth embankment.

According to W.I. Siriweera [1982], a specific set of rules and regulations governing the maintenance of irrigation works and the distribution of water seems to have existed in ancient Sri Lanka. For example, breaching the dam of a reservoir was considered an offence tantamount to a theft. There was also a well organized system of water distribution as it was necessary for every farmer to get an equal share of water during the periods of scarcity. The farmer's share of water was called "diyamura" and for this he had to pay a stipulated amount to the king, the local authority or the individual tank-owner. During the periods of drought, water was distributed in turns. Under such circumstances receiving water out of turn was considered a case of theft [Siriweera 1982].

However, in the middle of the thirteenth century, the hydraulic civilization based on the two major complexes as well as on the small village tanks which had spread over most parts of the dry zone virtually ended when the bulk of the Sinhalese population had drifted to the wet zone. In the middle of the nineteenth century a policy of restoration of the irrigation works was initiated by the British colonial administration.

S. Abeyratne and J. Perera [1986] reviewed the changes and continuity in irrigation management policies during the recent two centuries. The "vel vidane" system based on the Paddy Lands Irrigation Ordinance of 1856 played a very important role in irrigation system management until 1958. The "vel vidane" was an elected farmer representative. The primary duty of the "vel vidane" was to supervise the cleaning and maintenance of the irrigation channels at all times, but especially during drought, to ensure a fair distribution of water for irrigation.

S. Abeyratne and J. Perera [1986] pointed out several reasons why the "vel vidane" system worked satisfactorily:-

i) The "vel vidanes" originated from the villages and quite often belonged to the village elites. As the result they commanded a large measure of respect and power which allowed them to be effective even without recourse to the formal sanctions of their authority.

ii) They were accountable to the irrigators they were serving because they were appointed and directly compensated by the latter. As compensation was a share of the total production— 1/64 of the total harvest of each paddy holding in each cultivation season— it was in the vel vidane's interests to ensure maximum production, with water being delivered to the tail-end rather than at the head-end.

iii) The "vel vidanes" were always at hand and could take swift punitive action when the need arose [Karunanayaka 1981].

However, this traditional irrigation management system became attenuated and less prominent when the "vel vidane" system was abolished and the new Cultivation Committee (CC) system was introduced in 1958 under the Paddy Lands Act (PLA). To make matters worse, the CCs were not established in most of the rural areas until the early 1960's. This vacuum in irrigation leadership at the village level contributed to the deterioration of the village irrigation systems, especially with regard to maintenance. Also often the ex-"vel vidanes" who were not elected to the CC attempted to sabotage it.

The Agricultural Lands Law of 1973 superceded the PLA of 1958 and abolished the old CC system based on election. Instead, it introduced a new CC system with appointed members to function as village-level agents of a new divisional agrarian agency called the Agricultural Productivity Committee (APC). According to S. Abeyratne and J. Perera [1986], this move led to further deterioration of village-level irrigation leadership as the CC members were appointed by the politicians on the criteria of political popularity and the ability to deliver votes in an election.

The Agrarian Services Act of 1979 in its attempt to combine both the old "vel vidane" system and the Cultivation Committee system, established the Agrarian Services Committees (ASC). The members of the Committee were to be appointed by the Commissioner of Agrarian Services. The ASC consists of the Cultivation Officers who are public officers and the Farmer Representatives (FR) who are the village level agents and are normally addressed to as "vel vidane" by villagers. However, the new "vel vidane" has little power over irrigation matters and acts essentially as a mediator between farmers and the Cultivation Officer [Abeyratne and Perera 1986].

A series of studies carried out by S. Abeyratne and J. Perera [1984, 1986] demonstrated how the state penetration had contributed to a decrease of the importance of the irrigation system from a social point of view while conversely increasing its importance from an economic point of view, not the least because of the increased value which irrigation had given to paddy land.

In Sri Lanka, emphasis seemed to have been placed on studies on the management of irrigation systems based on political and socioeconomic aspects rather than on technical aspects.

Several papers are available as manuals of planning and design for irrigation systems. J.S. Kennedy [1933] contributed a paper entitled 'The evolution of scientific development of village irrigation works'. Subsequently W.A. Guthrie [1936] contributed a paper on the anti-silt measures for up-country irrigation canals. S. Arumugam [1957] published a very informative book entitled 'Development of village irrigation works'. A.J.P. Ponrajah [1984] published a book covering the hydrologic and hydraulic designs of irrigation headworks of reservoir and anicut schemes for catchments up to 20 square miles in size.

Studies on the management of major irrigation systems have been carried out continuously based on engineering aspects in some major schemes, such as the Kaudulla and Mahakanadarawa schemes. In the Kaudulla scheme, there are several studies on irrigation management including those of C.L. Abernethy [1985], D.W. Holmes et al. [1984] and J.A. Weller [1982, 1985].

In the Gal Oya Project, PRC Engineering Consultants Intl. [1984] studied water management and constructed a computer model. M. Svendsen and C.M. Wijayaratne [1982] examined the special pattern of water distribution in the Gal Oya left bank command and related water availability to paddy yield. In the study, they employed the Water Availability Index (WAI) which was computed using a simple system of weighting to indicate the degree to which water was available to crops during the 50-day critical period of plant growth (between 20 and 70 days before harvest). The study showed that while head-end areas have plenty of water, WAI drops drastically towards the tail of the system. Some tail areas are substantially rainfed. The WAI showed a high correlation with paddy yield. Most of the variation in yield could be accounted for by water alone. The location of the distributary channel is the most significant determinant of water availability. In areas with scarce water supply, farm location along the distributary channel is also significant unlike location along the field channel.

In the Mahakanadarawa scheme, hydrological studies include those of Y.K. Choo et al. [1981, 1982], C. Kariyawasam [1984] and K.A.T. Nikapitiya et al. [1975, 1977]. Y.K. Choo and G.G.A. Godaliyadda carried out a study on the rotational irrigation practice along with the early sowing policy which was adopted to utilize as much as possible the early seasonal rainfall. In this study, a 3 inch depth of water requirement at the field and 7 day rotation interval were adopted for the 1980/81 Maha rice cultivation. When rainfall amounted to 89mm a total of 623.5mm of water had been delivered from the tank to irrigate about 1,860ha, resulting in approximately 60% of project irrigation efficiency [1981].

In studies on the management of minor irrigation systems and on-farm water management, technical achievements include those of J.A. Lewis [1975, 1977], S. Somasiri [1981], S.H. Upasena [1982] and N. Vithanage [1982]. J.A. Lewis studied the on-farm supplementary irrigation requirement for rice at the Maha Illuppallama Agricultural Experimental Station [1975].

S.H. Upasena carried out an important experiment at the Walagambahuwa minor village tank in Anuradhapura district [1982]. He evaluated the water balance and rainfall-runoff characteristics in the catchment of a typical minor tank. During the 1978/79 Maha season, about 35% of the total tank storage increment was associated with direct rainfall. The average runoff percentage to the runoff associated with rainfall was about 25%. During the months of February and March, evaporation and seepage losses were 7.5% on the average. The average tank seepage appeared to be about 2mm/d. The author analyzed the cropping systems practiced in a typical minor tank scheme. Usually the tank storage is completely used up by the rice crop which is harvested in April, and a second crop of rice or upland crops are seldom grown with tank irrigation. Even the cultivation of a first crop of rice grown late in the Maha season using a three month variety of rice is unsuccessful. Probability of success in the cultivation of a rice crop is once in four or five years [Upasena 1982].

These results enable to understand why a large number of minor tanks are abandoned in the dry zone. Obviously, water resource development for rice cropping based on clusters of minor village tanks appears to exceed the hydrological capacity in the dry zone as suggested by H. Nakamura [1986]. Namely, a large number of cascade tank systems seemed to have been developed in succession based on the water condition of a wet year instead of that of a dry year. Such over-developed tank irrigation systems frequently bring about poor paddy production not only in dry years but also even in normal years. Therefore, typically, village tank systems allow land use pattern of paddy followed by shifting cultivation of upland crops, that is adapted to the dry zone environment. Shifting cultivation locally referred to as "chena" is practiced in the tank watershed and other upland areas. "Chena" cultivation is devoted mainly to the production of upland crops and is not only an insurance against paddyd failure but in itself contributes significantly to the family income and diet [Abeyratne and Perera 1986].

Recently, Sri Lanka, which is rapidly approaching self-sufficiency in rice, has placed emphasis on the management of irrigation systems for crop diversification. This type of research was started and is being carried out by researchers not only at the International Irrigation Management Institute (IIMI) [Miranda and Panabokke 1987, Panabokke et al. 1987] but also at the Irrigation Department [Dimantha 1987] and the Department of Agriculture [Somasiri 1981]. IIMI's studies on this subject have the following principal objectives [Miranda and Panabokke 1987] :-

i) To determine existing and potential irrigation management practices for non-rice crops at the main system, tertiary, and farm/field levels,

ii) To identify the constraints to diversified cropping under irrigation,

iii) To identify ways to alleviate such constraints, and

iv) To identify field tests for practices to maximize the effectiveness and profitability of irrigation of selected non-rice crops.

Though studies have been initiated only recently in collaboration with national institutions in Sri Lanka, great results are anticipated in the future.

III. Natural environment and current conditions of rice double cropping in the investigation areas

1. Muda Irrigation Scheme

1.1 Natural environment

1) General condition

The Muda Irrigation Scheme covers a total gross area of 126,000ha of which 96,000ha are under the cultivation of paddy. It is the largest rice double cropping area in Malaysia. The area is located at about 5° 45′~6° 30′N latitude and 100° 10′ ~100° 30′E longitude in the vast flat alluvial Kedah-Perlis Plain about 20km wide and 65km long between the foothills of the Central Range and the Straits of Malacca. The area is generally flat with slopes of 1 in 5,000 to 1 in 10,000 ranging from +4.5m in elevation in the inland fringe to +1.5m in elevation in the coastal area [Muda Agricultural Development Authority 1977]. Fig. III-1 shows a general map of the Muda Irrigation Scheme.

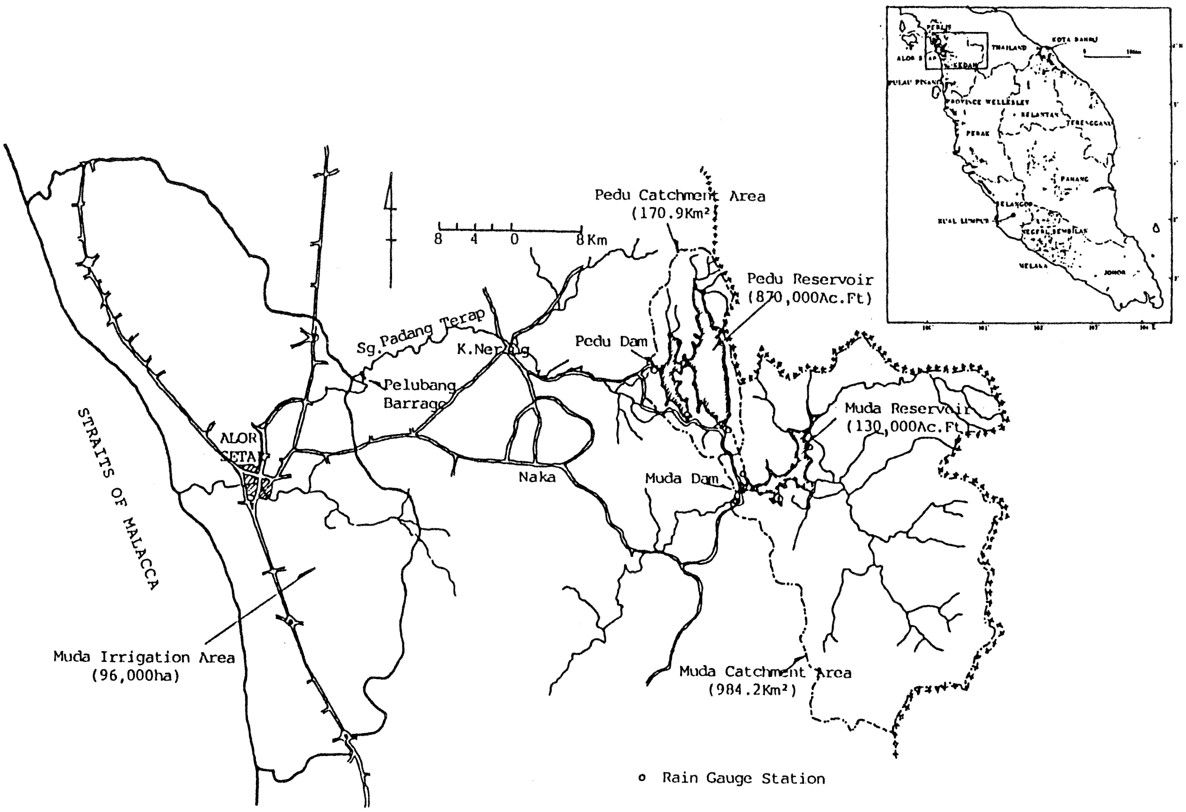


Fig. III—1 General plan of the Muda Irrigation Scheme, Malaysia.

2) Climate

The major part of Peninsular Malaysia is characterized by a tropical rainforest climate. However, only the Muda area and its periphery where there is a pronounced dry season are under the tropical monsoon climate as the areas are shielded from the rain-bearing winds of the Northeast monsoon and the Southwest monsoon by the Central Range and Sumatra, respectively. The bulk of the rainfall in the area is brought by the intermonsoon rains [Muda Agricultural Development Authority 1977]. The distribution of the recent 38-year average monthly rainfall at Alor Setar Airport (Kepala Batas) is shown in Fig.III-2. The average monthly rainfall shows two maxima: a higher maximum in September-October, of about 300mm and a lower maximum in May, of about 250mm. December-March are the dry months with an average monthly rainfall of less than 100mm. The annual rainfall characteristics enable to identify three seasons, namely the dry season from December to March, the moderate season from April to July and the wet season from August to November.

Mean monthly temperature varies between 25.9℃ in November and 28.1℃ in April.

Mean monthly relative himidity ranges from 71% in February to 87% in October [Muda Agricultural Development Authority 1977].

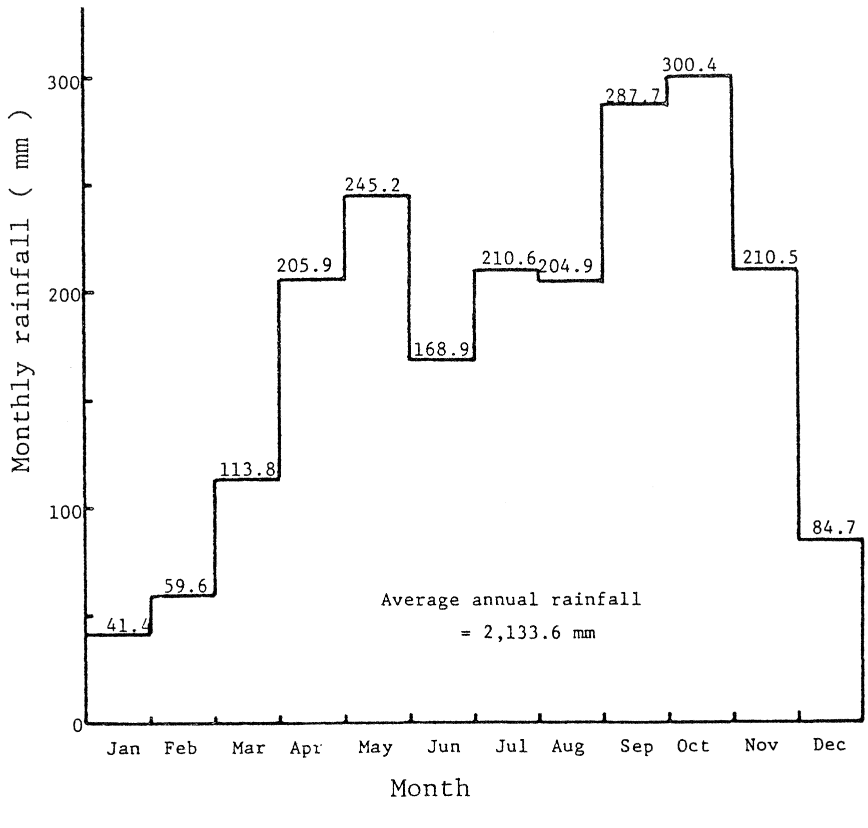


Fig. III—2 38 year average monthly rainfall in Kepala Batas (1947 -1984), Muda Scheme, Malaysia.

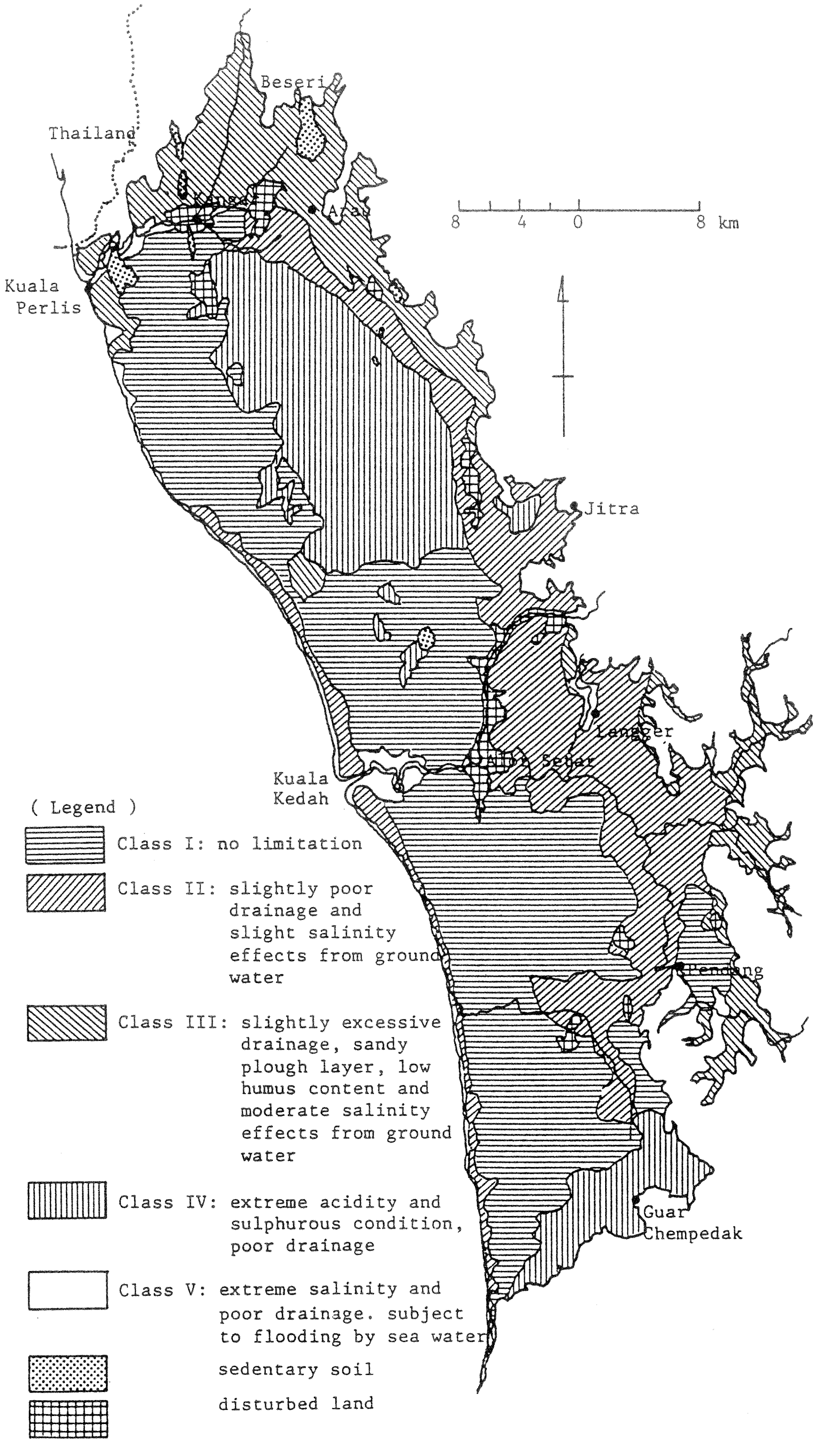


Fig. III—3 Soil class map of the Kedah-Perlis coastal plain, Malaysia [Soo 1972].

3) Soils

The soils in the Kedah-Perlis Plain consist of heavy clay. The majority of their parent materials is composed of marine sediments deposited during the rise in sea level in the Pleistocene era. The other parent materials include riverine sediments [Soo 1972, Kawaguchi and Kyuma 1969]. Zones of marine and riverine sediments can be bounded approximately by the trunk railway line running parallel to the coast line.

While the land efflorescences carried to the sea had been deposited on the seabed, these sediments were replenished with base and silicic acid, and are rich in mineral and chemical substances [Furukawa 1976]. Therefore, this plain is comparatively fertile. Regarding the clay mineral composition, soils derived from marine sediments are more montmorillonitic than those derived from riverine sediments [Furukawa 1976].

The soils reclaimed from a "gelam" tree swamp about 33 years ago were highly acid and contained large quantities of sulphur compounds (Fig.III-3) [Soo 1972]. These soils known as acid sulphate soils had brought about great damage to paddy cultivation, especially in dry years [Furukawa 1976]. Until they have been gradually improved by irrigated paddy cultivation in the Muda Irrigation Project, and today the damage no longer occurs.

Soils in the Muda area become very hard and compact during the non-irrigation period, and they crack markedly. When they are saturated with water, the cracks are filled up due to swelling and slaking phenomena, and their permeability decreases rapidly. Therefore, these soils are unfit for upland field cropping but very suitable for paddy cultivation.

1.2 Conditions of rice double cropping and management of irrigation systems

History of rice double cropping is comparatively recent in the Muda area. It was introduced only in 1970 after the completion of the Muda Irrigation Project (Muda I Project: 1966-1970), prior to which only rainfed single cropping had been possible. The principal components of the project are as follows [Muda Agricultural Development Authority 1977] :-

(i) Two dams — the Muda (buttress type) and Pedu (rockfill type) dams creating two reservoirs which are connected by a 6.6km tunnel, with a total storage capacity of $1,209 \times 10^6 m^3$,

(ii) A conveyance system comprising a river channel about 67km long, a diversion barrage (headworks), a bifurcation-regulator structure, 11 radial gate regulators and 116km of main canals,

(iii) A distribution system comprising 970km of secondary canals 1.2 to 2.0km apart from each other (canal density: 10m/ha), 870km of drainage channels (drainage density: 9m/ha) and 24 pumping stations,

(iv) Coastal bunds with a total length of 100km and 25 tidal gates along the length to prevent tidal ingress and facilitate drainage of flood and excess water,

(v) Laterite-covered farm roads with a total length of 780km (density: 8m/ha).

The historical record of the annual cropping area and yield per hectare in the Muda area is shown in Fig.III-4 [Jagatheesan 1987]. In 1985, the annual rice production amounted to 806,900 tons or 41.3% of the total production in Malaysia [Berita Publishing 1987]. However, the area is still facing some problems for the implementation of stable rice double cropping. One of the major problems is the considerable delay in the distribution of irrigation water for saturation and flooding of the

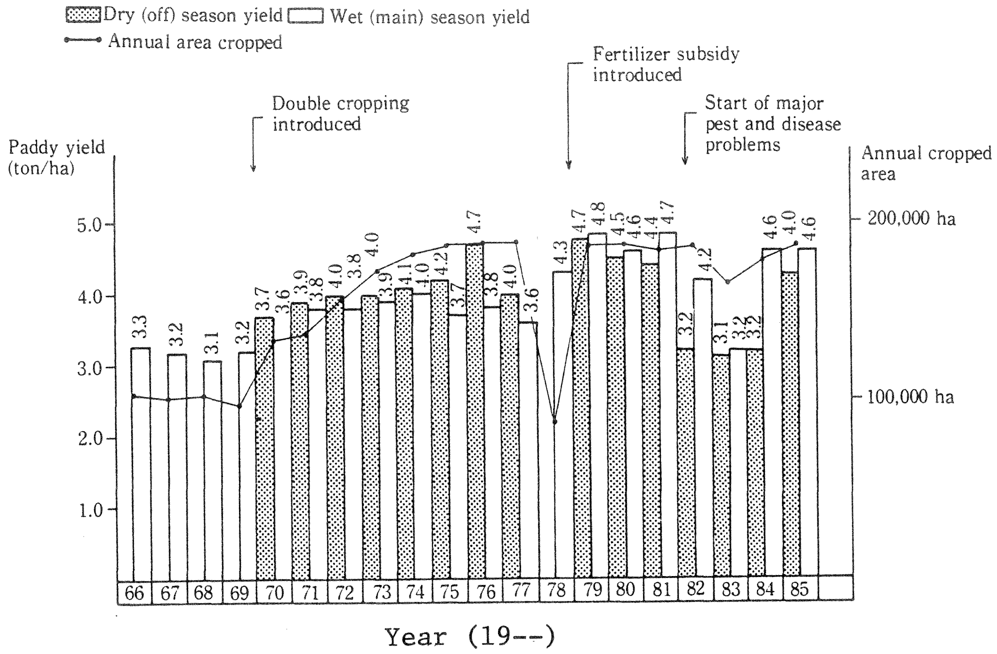


Fig. III—4 Record of paddy yield and annual cropped area in the Muda Scheme, Malaysia [Jegatheesan 1987]

paddy fields during the presaturation*) period. This is caused by the low canal density at a level of 10m/ha in an area with an extremely flat topography with a slope of 1 in 5,000 to 1 in 10,000, which leads to a considerable loss of irrigation water. Moreover, the delay in presaturation was responsible for erratic cropping schedules and the continuous presence of the rice plant, which is the major host plant of insect pests, hence the severe damage caused by diseases and insect pests. In addition, the erratic cropping schedules coupled with the rapid dissemination of heavy farm machines resulted in the deterioration of the load bearing capacity of the paddy soil.

In order to solve this problem, the Tertiary Development Project (Muda II Project: 1976-1990) has been implemented aiming at increasing the canal density from a level of 10 m/ha to 30-35 m/ha. The main purpose of the Muda II Project is to improve water distribution and to decrease the water requirements by shortening the presaturation period by the increased canal density. However, the effect on rice cropping has not been demonstrated due to inadequate management of the tertiary system.

The management of irrigation systems in the Muda area is carried out by the Muda Agricultural Development Authority (MADA) which is the statutory body under the Ministry of Agriculture. The Muda area is divided into 4 districts, namely Districts

*) Presaturation: In this paper, presaturation is defined as the supply of water, either by irrigation or rainfall, to paddy fields so as to wet the ground to saturation and to provide enough water to facilitate ploughing and preparation of nursery beds [Thavaraj 1975].

1,2,3 and 4. The various irrigation and drainage facilities under each district are operated and maintained by the district engineer's office. Every district engineer's office is staffed with a district engineer, a deputy district engineer, technicians, irrigation inspectors (IIs), irrigation overseers (IOs) and line operators (LOs). The control center which manages important structures such as dams and headworks, and gives instructions to every district engineer's office is located at the headquarters of MADA.

An irrigation block is a rectangle-shaped area of 200 to 810ha irrigated by a secondary canal (Fig.III-5). There are 110 irrigation blocks in the Muda area. To every irrigation block a LO is assigned for the operation of the secondary system. A few LOs are supervised by an IO, and several IOs are under the supervision of an II. The duties of these field staffs are shown in Fig.III-6.

In the tertiary development area, an irrigation block is divided into 6 to 10 irrigation service areas (ISAs). An ISA covers an area of 80 to 200ha which is

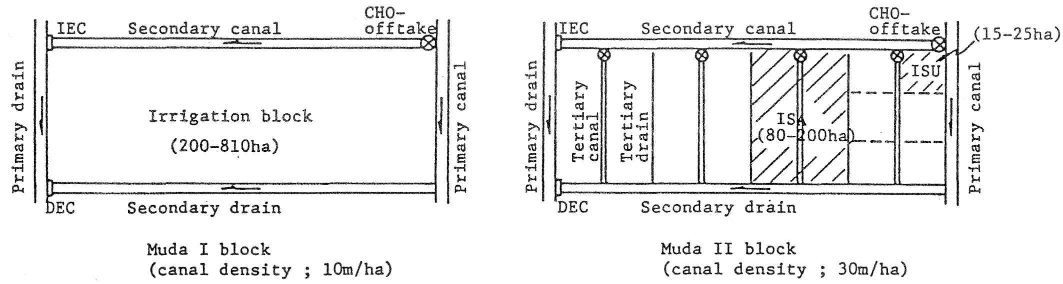


Fig.III—5 Concept of Muda I and Muda II blocks

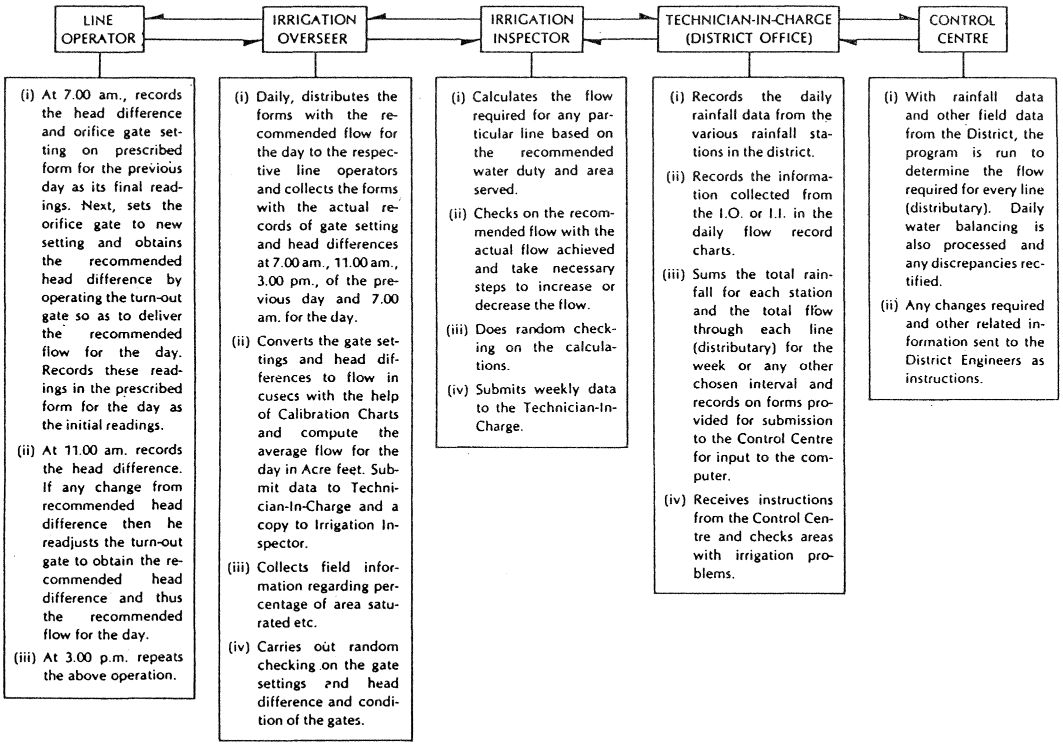


Fig.III—6 Duties of field staffs, Muda Scheme, Malaysia.

irrigated by a tertiary system, and is divided farther into 5 to 6 irrigation service units (ISUs). An ISU covering 15～25ha is the minimum unit for irrigation schedule (Fig. III-5).

Irrigation facilities up to the secondary system including the tertiary offtake are maintained by MADA. However, the management of the tertiary system except for the tertiary offtake is generally entrusted to the farmers. Therefore, in implementing the tertiary development, the farmers have the duty to organize their committee for the operation and maintenance of the system. An ISU Committee is established in each ISU. In each ISA, an ISA Committee is organized by the leaders of the ISU Committees. An Irrigation Block Committee consists of all the leaders of ISA Committees in the block. However, since the performance of these committees is very limited in the tertiary development areas, the usefulness of the tertiary systems has not been clearly demonstrated yet.

2. Dry zone area of Sri Lanka

2.1 Natural environment

1) General conditions

Sri Lanka is an island set in the Indian Ocean. Its area which is 65,609km^2 is about the same as that of Hokkaido Island. It is located at 5° 55′～9° 50′N latitude and 79° 42′～81° 53′E longitude and lays entirely in the tropical zone. The terrain slopes from the south-southwest towards the north-northeast. High mountains of more than 1,500m in elevation are concentrated in the center of the southern half of Sri Lanka. Rivers run radially from the mountainous area to the sea. The island can be divided into two climatic zones, namely the dry zone occupying three-fourths of the island in the northern part and the wet zone occupying the rest. Hilly and mountainous areas with an elevation of more than 150m belong to the wet zone, and the dry zone is composed of low peneplains less than 150m in elevation and coastal plains. The majority of the peneplains is covered with forests. Fig. III-7 shows the relief of Sri Lanka [Cooray 1967].

2) Climate

Rainfall is very much affected by the southwest monsoon and the northeast monsoon in Sri Lanka. The southwest monsoon starts in May when the north conveyance zone moves up to the north from the island and lands in South India. Then, the monsoon becomes active due to the influx of wet air from the Indian Ocean into the dry and hot air current ascending from the heated inland areas of India. The humid wind from the Indian Ocean is shaded by the southwest slopes of the mountainous area and brings about much rain in front of the mountains. However, it changes into dry and hot wind after going over the mountains due to the foehn phenomenon, and brings hot weather to the northeast areas of the island. The southwest monsoon brings little rainfall, less than 20 inches (508mm), to the dry zone [Dept. of Meteorology 1969]. This monsoon season is called Yala season in Sri Lanka. This monsoon is over in about September.

The northeast monsoon starts in about November when the north conveyance zone moves down to the south of the island and stays around the equator. The continental air mass becomes very humid while it is passing through the Bay of Bengal and brings about much rain to whole island. The north conveyance zone moves down to

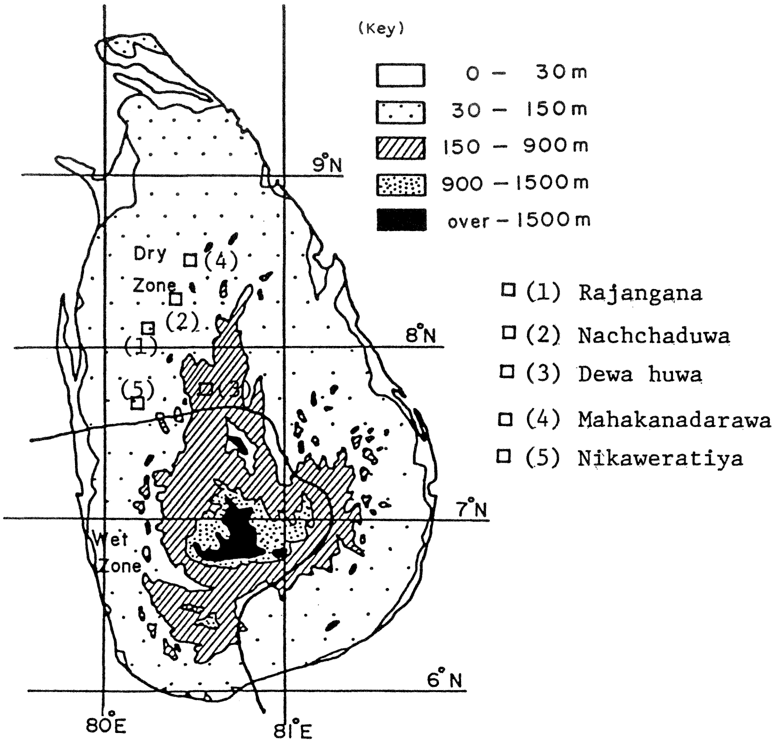


Fig. III—7 Sketch map of the relief of Sri Lanka [Cooray 1967].

Table III—1 Average monthly air temperature (upper line ; in ℃) and average monthly rainfall (lower line ; in mm) at several stations in Sri Lanka.

Zone	Station	Latitude (N) / Longitude (E)	Altitude (m)	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.	Year
Dry Zone	Anuradhapura	8°21′	89	24.6	25.7	27.5	28.4	28.7	28.4	28.6	28.6	28.7	27.3	25.9	24.8	27.3
		80°25′		147	43	107	163	89	18	33	40	97	246	272	191	1448
	Maha Illuppallama	8°07′	137	24.7	25.5	27.6	28.2	28.4	28.2	28.1	28.3	28.7	27.2	25.8	24.8	27.2
		80°28′		140	49	117	185	107	34	35	40	76	241	253	204	1481
	Trincomalee	8°35′	7	25.6	26.2	27.3	28.7	29.8	29.9	29.7	29.4	29.3	27.8	26.3	25.7	28.0
		81°15′		211	95	48	77	68	18	54	103	89	235	355	374	1727
	Jaffna	9°39′	3	25.3	26.1	27.9	29.4	29.4	28.8	28.3	28.1	28.2	27.6	26.4	25.4	27.6
		80°01′		112	38	40	56	51	10	15	28	64	234	439	264	1349
	Puttalam	8°02′	2	25.4	26.2	27.4	28.2	28.7	28.3	27.9	27.9	28.1	27.2	26.3	25.6	27.3
		79°50′		86	36	79	125	97	36	25	15	40	188	257	142	1126
Wet Zone	Colombo	6°54′	6	26.2	26.4	27.2	27.7	28.0	27.4	27.1	27.2	27.2	26.6	26.2	26.1	26.9
		79°52′		88	96	118	260	353	212	140	124	153	354	324	175	2397
	Ratnapura	6°41′	46	26.8	27.4	28.0	28.1	27.7	27.1	27.0	26.9	26.9	26.7	26.7	26.6	27.2
		80°24′		160	135	264	295	531	472	325	290	368	457	376	231	3901
	Kandy	7°20′	480	23.1	23.8	25.3	26.0	25.7	24.7	24.2	24.4	23.9	24.8	24.0	23.2	24.4
		80°38′		170	61	137	152	165	185	150	119	152	295	272	226	2088
	Nuwara Eliya	6°58′	1880	14.1	14.1	14.8	16.4	16.6	15.9	15.6	15.7	15.6	15.4	15.2	14.7	15.3
		80°46′		170	43	109	119	175	277	300	196	226	269	241	203	2332

Source: Studies on agricultural environment (meteorological condition) in Southeast Asia the south of the island in about October, however, it takes time for moving down to the south compared with moving up to the north. Therefore, the northeast monsoon is more variable than the southwest monsoon and its starting time varies from year to year. This monsoon season is called Maha season.

There are convectional rains peculiar to the tropics between the two monsoon seasons, i.e. in April and October.

Boundary of the wet and dry zones seems to have been fixed by the isohyet for an annual mean rainfall of 75 inches (1,905mm) or southwest monsoon rainfall of 20 inches (508mm) [Dept. of Meteorology 1969].

The annual mean temperature is around 27~28℃ in the dry zone. Its annual variation is only 4.1℃ in Anuradhapura, however, the variation is still smaller in the wet zone, e.g. 1.9℃ in Colombo, 1.5℃ in Ratnapura. The daily variation in temperature is 3~8℃ in the coastal area (Trincomalee) and 6~10.5℃ in the inland area (Anuradhapura). Monthly mean temperature and monthly mean rainfall at several stations are indicated in Table III-1 [Tropical Agriculture Research Center].

Based on the Köppen's climate classification, the dry zone comes under As_1 or As_2, that is tropical savanna-like monsoon climate. The wet zone comes under Am_{ws}, namely tropical rainforest-like monsoon climate [Tsuchiya 1964]. In the dry zone, the annual potential evapotranspiration calculated by the Thornthwaite method is 1,600~1,800mm, and the water shortage amounts to 200~700mm during the dry season [Tropical Agriculture Research Center]. Therefore, from an agricultural viewpoint, emphasis should be placed on the importance of irrigation which enables to overcome the water shortage for the development of the dry zone.

3) Soils

The soils of which parent materials are metamorphic rock and igneous rock mainly composed of gneiss and granite, respectively are widely distributed in Sri Lanka. According to C.R. Panabokke and F.R. Moormann [1967], the soils can be divided into soil groups as shown in Fig.III-8. It is obvious from Fig.III-8 that the dry zone is covered with soil groups mainly composed of Reddish brown earths. However, these soil groups are hardly distributed in the wet zone.

Generally, the configuration of the dry zone consists of countless gentle undulations. Reddish brown earths are distributed over the upper part of each undulation, and low-humic grey soils cover the lower part of it, respectively. In Fig.III-8, classification 1 shows the extent covered with these soil groups. Sometimes yellowish brown earths can be seen between reddish brown earths and low-humic grey soils in an undulation.

(i) Reddish brown earths:

This soil group is well-drained and indicates some reaction of weak acidity, neutrality, and weak alkalinity. This group is poor in nitrogen and phosphorus but rich in potassium, calcium and magnesium. Cation exchange capacity of this soil group is 50me/100g, which is favorable for agriculture. If only water were secured, this soil group could be suitable for paddy and fruit cultivation.

(ii) Low-humic grey soils:

This poorly-drained soil group is distributed over the lowland and has a B horizon including clear mottling. This group is fertile, and indicates an alkaline reaction. If only water were secured, this soil could be suitable for paddy cultivation.

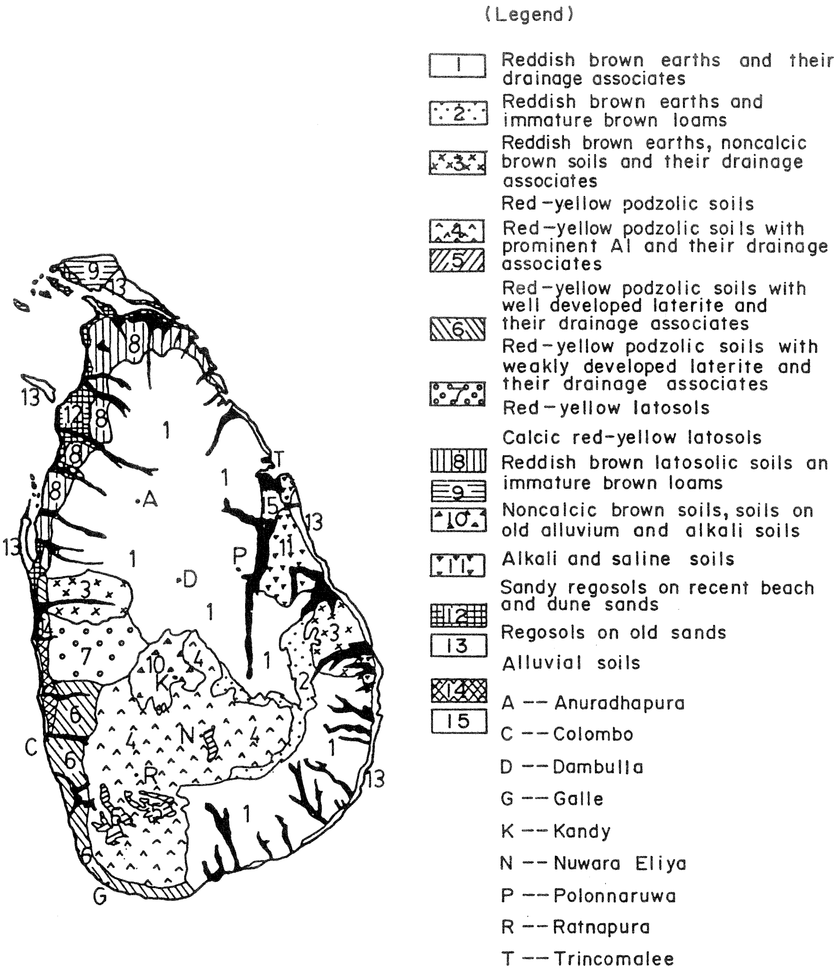


Fig. III—8 **Soil map of Sri Lanka [Panabokke and Moormann 1967].**

2.2 Current conditions of rice double cropping and management of irrigation systems

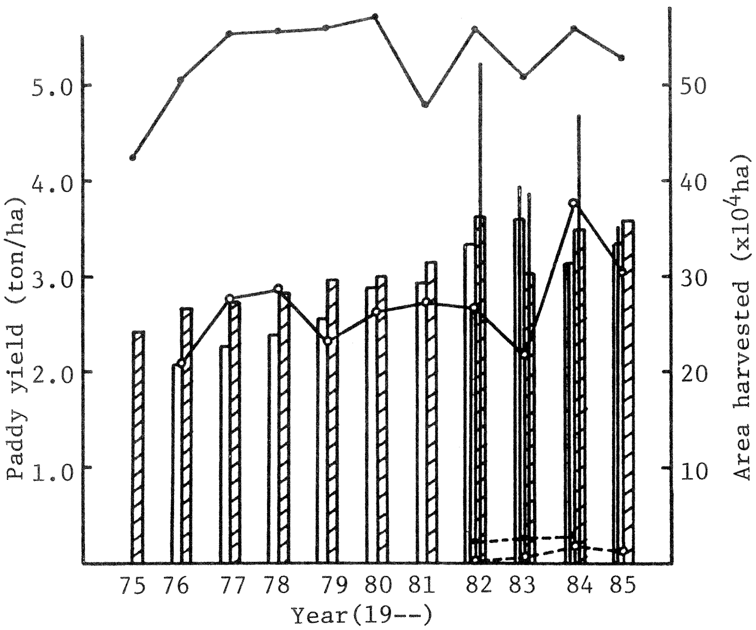
In the dry zone area of Sri Lanka, due to the traditional and effective use of water resources, irrigated rice cropping culture was prosperous from olden times. Especially, it is characterized by water usage based on a cluster of reservoirs (tanks) linked with each other and sometimes extending over a few river basins. It is said that the framework of the existing large-scale irrigation systems in the Kala Oya (River) and Mahaweli Ganga (River) Basins had already been established by the middle of the seventh century A.D. [Brohier 1934]. The ancient irrigation facilities were built with wonderful technology, for example, the Jaya Ganga built by King Dhatusena in the 5th century A.D. which aimed at carrying the waters of the Kala Wewa (Tank) to the ancient city tanks of Anuradhapura, 92km away, while feeding a number of village tanks in its course [Brohier 1934]. This channel is also famous for the gentle gradient of 1 in 10,560 for the first 27km and an average of 1 in 5,280 throughout its length [The People's Bank Research Department 1977]. These ancient irrigation systems were rehabilitated and expanded repeatedly by the successive kings during the Anuradhapura and Polonnaruwa eras. However, they had been abandoned and covered with jungle after the transfer of the capital to the wet zone due to the continuous struggles with the Tamil dynasty, which was increasing its power in the northern part of the country during the latter half of the 13th century, through the colonial domination by Portugal and Holland until their importance was recognized during the latter half of the 19th century under the British domination. The existing irrigation systems were rehabilitated and expanded by the Irrigation Department based on the agricultural policy centered on the rehabilitation project for the abandoned ancient systems and the colonization scheme in the dry zone after the independence in 1948.

All the irrigation works which are within the jurisdiction of the Irrigation Department can be divided into two groups, i.e. major irrigation works and minor irrigation works (or village irrigation works). The former are large-scale projects with a benefited area of 80ha which are implemented and maintained by the Irrigation Department. The latter are small-scale projects based on farmers' voluntary activities with a benefited area which does not exceed 80ha extending over one or two villages. In the major irrigation works, the irrigation and cultivation schedules are supposed to be decided in the farmers' meetings, but practically, the decision is made during deliberations among the governor, officers in charge from the Irrigation Department and Department of Agriculture, and Colonization officers. Meanwhile, all the matters related to the irrigation systems and cultivation are traditionally managed by the farmers in the minor irrigation works [Nakamura 1976]. In the areas under the minor irrigation works, a village is formed based on a tank and its irrigation systems. It has been said, that 'A tank means a village and a village means a tank'. The tank is the provider of all the material needs of village life, when a tank breaches the village migrates [Arumugam 1967]. Accordingly, a large number of customs related to the management of irrigation systems seem to have existed in ancient times. Even now, when the amount of water stored in the tank is not sufficient for the entire benefited area, an interesting and rational custom called "betma" is exercised in these areas. In this custom, all the farmers cultivate only the irrigable area estimated by themselves based on the amount of water stored in the tank prior to the onset of irrigation, and distribute the crops harvested among themselves in proportion to the land owned by the individuals in the entire benefited area.

Among the major irrigation works, the Mahaweli Development Scheme is the largest one. This scheme is a comprehensive water resources development of the Mahaweli Ganga, Sri Lanka's largest and most important river, for the irrigation of 223,000ha (new land: 158,000ha, existing land: 65,000ha) in the dry zone, and the generation of a power capacity of 550MW in the first phase and the accelerated programme. Up to now, major structures, such as the Polgolla headworks, Bowatenna, Kotmale, Victoria, Randenigara, and Maduru Oya dams, except some main canals, have been completed. It is anticipated that about 140,000 families from the wet zone will settle in this scheme. The extraordinary enthusiasm of the Sri Lankan government for the irrigation development of the dry zone was reflected in the establishment of the Ministry of Mahaweli Development in 1979.

The historical record of the annual harvested area and yield per hectare in Sri Lanka is shown in Fig. III-9 [Department of Census and Statistics 1986]. In recent years, the average yield was 3.3t/ha for the Yala season and 3.4t/ha for the Maha season. It is estimated that the annual harvested area of the dry zone accounts for

70% of the country's gross area of paddy cultivation, and that the yield is 10 to 15% higher than the country average. In the reclaimed paddy land in the Mahaweli Scheme, the average yield is estimated at 3.3t/ha for the Yala season and 4.6t/ha for the Maha season.



(Legend)

Gross paddy yield of Yala season crop(including Mahaweli area)
Gross paddy yield of Maha season crop(- do -)
Gross paddy yield in Mahaweli area
Harvested area of Yala season(including Mahaweli area)
Harvested area of Maha season(- do -)
Harvested area of Yala season in Mahaweli area
Harvested area of Maha season in Mahaweli area

Fig. III—9 Paddy cropping area and yield in Sri Lanka.

IV. Water management in irrigation area

1. Mechanism of water consumption and water requirement in terminal paddy fields

It is very important for the planning and the management of irrigation schemes to clarify the mechanism of water consumption in terminal paddy fields. In Japan, this type of research has been carried out by many workers, and methods for the investigation of water requirement of paddy fields have been developed by S. Nakagawa [1966, 1967], R. Kaneko et al [1968, 1973, 1971]. However, there is only a limited number of studies in this field in the tropical monsoon area.

In Malaysia, special attention should be paid to the studies carried out by S. Nakagawa et al [1960], Van de Goor et al [1963], K. Sugimoto [1971], and S. Yashima [1982, 1986]. These works were based on stationary conditions without taking time series into account, and information on the effective rainfall and irrigation efficiency was not obtained. In the dry zone area of Sri Lanka, this type of research was started by T. Murakami [1966, 1967], followed by some Sri Lankan researchers in the Maha Illuppallama Agricultural Experimental Station [1975].

In terminal paddy fields, the mechanisms of water consumption and water requirement depend on the topography, climate, soil, canal density, irrigation method, etc. Fig.IV-1 shows the movement of water in paddy fields where plot-to-plot irrigation is adopted. The water balance in paddy fields between the inlet and the outlet is expressed by the following equation:-

$$IR+RF=VS+ET+(G_2-G_1)+RO=VS+ET+P+S+RO \quad \cdots\cdots\cdots (IV\text{-}1)$$

Where IR : irrigation supply
RF : rainfall
VS : variation in the amount of stored water in fields
ET : evapotranspiration
P : percolation
S : seepage
RO : surface runoff
G_1 : inflow of groundwater into fields

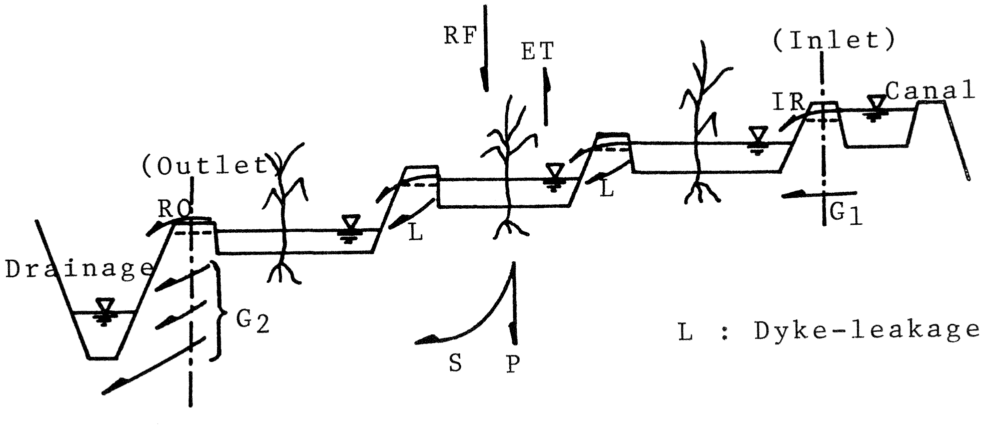


Fig.IV—1 Water movement in plot-to-plot irrigation fields.

G_2 : outflow of groundwater from fields

$(G_2\text{-}G_1)=S+P$

Actually, it is difficult to separate $(G_2\text{-}G_1)$ into P and S quantitatively in practical fields. In this paper, P and S are defined as follows:-

P: amount of water lost as $(G_2\text{-}G_1)$ without returning to drainage system

S: amount of water lost as $(G_2\text{-}G_1)$ returning to drainage system

In this Chapter, the mechanisms of water consumption and water requirement in terminal paddy fields are discussed together with the coefficients of effectiveness for irrigation and rainfall based on the on-site studies carried out in the Muda Scheme of Malaysia and the dry zone area of Sri Lanka.

2. Case study in the Muda Scheme, Malaysia

2.1 Study area

The tertiary development in the SCRBD5b irrigation block which was completed in 1982 during the first phase of the Muda II project is divided into 8 Irrigation Service Areas (ISAs), i.e. ISAs A,B,C,…, H. As a study area, ISA A covering 136.8 ha was selected. The study area of ISA A, SCRBD5b lies in the south-western part of the Muda irrigation area and is located approximately 20 km south of Alor Setar.

The study area is divided into 6 Irrigation Service Units (ISUs), namely ISUs A1, A2,A3,A4,A5 and A6 covering 28.3ha, 21.9ha, 25.1ha, 15.8ha, 26.7ha and 19.0ha, respectively. The area is nearly flat but generally sloped down from the south to the north with ground levels ranging from +2.1m MSL to +1.5m MSL. The average ground level is about +1.85m MSL. The area is bounded on the south by the bund of the secondary canal SCRBD5b, on the east by the bund of the tertiary drain SD1/R2C and the secondary canal SCRBD5b, on the north by the bund of the

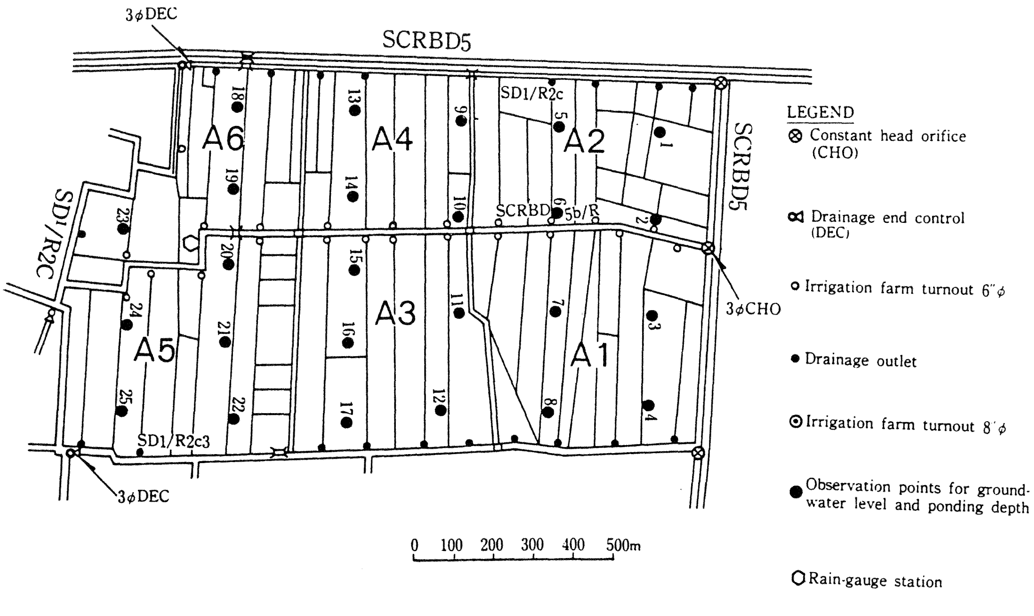


Fig. IV—2 Plan of ISA A, SCRBD 5b (136.8ha), Muda Scheme, Malaysia.

tertiary drain SD1/R2C, and on the west by the bund of the tertiary drain SD1/R2C3. The canal density of the study area is 24.6m/ha, and the drain density is 30m/ha. A plan of the study area is shown in Fig.IV-2.

The annual rainfall in the study area is comparatively high and averages about 2,450mm. The rainfall, however, is not evenly distributed throughout the year because of the tropical monsoon climate. The average monthly rainfall shows two maxima: a high maximum in September-October, when it reaches about 400mm and a lower maximum in May, when it reaches about 300mm. January and February are the dry months with an average monthly rainfall of less than 60mm. March and December are also relatively dry months with an average monthly rainfall of about 85mm.

Soil is marine alluvial clay of the Chengai Series, generally fertile. This soil is considered to be highly suitable for paddy cultivation on account of its heavy texture, generally fairly high nutrient content and flat topography [Soo 1972].

2.2 Water control system

The design of the Muda II system aims at the completion of the presaturation of each ISU in a period of 7 days (1 week). Since the ISA A comprises of 6 ISUs, the complete presaturation of the study area can be achieved within 6 weeks by sequential presaturation. Each ISU is to be supplied at a presaturation rate of 41.5mm/d for one week, at the end of which the supply is to be cut down to a supplementary rate of 7.6mm/d. The presaturation supply is then transferred to the next ISU. Table IV-1 shows the presaturation and supplementary irrigation schedule for ISA A based on the design of the Muda II system [Drainage and Irrigation Department 1982]. During the growing period of rice plants, the area is supplied at a growth requirement rate of 8.6mm/d [MADA 1977].

2.3 Factors influencing water balance

1) Irrigation supply

The irrigation supply was measured at the 3 feet-CHO (constant head orifice) offtake of SCRBD5b/R2, in which the opening of the orifice gate was continuously monitored and the differential head on the orifice gate was continuously recorded

Table IV—1 Presaturation and supplementary irrigation schedule of ISA A (Simultaneous presaturation of main field and nursery plot), Muda Scheme, Malaysia.

Week	Corresponding days	Presaturation (duty=41.5 mm/d)			Supplementary irrigation (duty=7.6 mm/d)			Total Q m³/s
		ISU No.	Area ha	Q m³/s	ISU No.	Area ha	Q m³/s	
1	1— 7	A1	28.3	0.136	—	—	—	0.136
2	8—14	A2	21.9	0.105	A1	28.3	0.025	0.130
3	15—21	A3	25.1	0.120	A1 to A2	50.2	0.044	0.164
4	22—28	A4	15.8	0.076	A1 to A3	75.3	0.066	0.142
5	29—35	A5	26.7	0.128	A1 to A4	91.1	0.080	0.208
6	36—42	A6	19.0	0.091	A1 to A5	117.8	0.103	0.194
7	43—49	—	—	—	A1 to A6	136.8	0.120	0.120

using a differential head recorder designed by TARC. The calibration curve showing the relationship among gate opening, differential head and offtake discharge was adopted for the calculation of the water supply.

2) Precipitation

The precipitation was observed at the rain-gauge station as shown in Fig.IV-2.

3) Pan-evaporation (Ep)

Ep was observed at the rain-gauge station by using a round black evaporation pan with a diameter of 120cm, which is commonly used by the Drainage and Irrigation Department (DID). In order to remove the influence of rainfall and to improve the observation accuracy on rainy days, a small water gauge with a float chamber was attached to the evaporation pan.

4) Evapotranspiration (ET) and evaporation from soil surface (Es)

According to S. Yashima's study [1982] on ET carried out in the ACRBD 4 irrigation block, the ratio of ET to Ep (ET/Ep) varies according to the same pattern irrespective of season. However, the pattern of the ET/Ep ratio is different between transplanting culture and direct sowing culture due to the difference in the plant growing process between them. In this study, ET was estimated by using the ET/Ep ratio proposed by S. Yashima, and Ep values observed in the study area.

Es was also estimated by adopting the Es/Ep ratio for heavy clay soil at various groundwater levels which was calculated by S. Yashima in 1974.

In taking account of the groundwater table, field activities and plant growing stages, the compound ET ratio which refers to the average ET/Ep ratio including Es in the study area was calculated.

Daily ET was obtained by multiplying Ep by the compound ET ratio.

5) Groundwater level and ponding depth

Groundwater level and ponding depth were calculated daily by manual measurements in 25 observation points which were distributed more or less evenly in the study area. It was assumed that the 25 observation points were representative of the whole study area in terms of groundwater level and ponding depth. The above-mentioned Es can be estimated based on the groundwater level, and the total existing water*) defined below can also be estimated from the groundwater level and ponding depth.

6) Total existing water (TEW)*) in fields

In this study, TEW includes not only the standing water on the field surface but also the existing water in the soil from the surface down to the 100cm depth.

Based on a field experiment carried out in the Telok Chengai Experimental Station by S. Yashima in 1974, the existing water in the soil can be estimated from the groundwater level by using the relationship mentioned above. Since the soil in the study area belongs to the same soil series as the soil in the Telok Chengai Experimental Station which is classified as the Chengai Series, the relationship obtained by S. Yashima was adopted in this study.

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*) Total existing water (TEW): a new terminology proposed by S. Yashima [1982]. TEW= (Existing water in the soil from the surface down to the 100 cm depth) + (Ponding depth)

When the soil is soaked completely, the amount of existing water in the soil is 85mm. After the field surface is flooded, the amount of TEW reaches 85mm in addition to the ponding depth.

7) Drainage discharge

The drainage discharge was measured at one drainage end control (DEC) of the tertiary drain SD1/R2C. The DEC serves an area of 48.0ha including ISUs A2, A4, and most part of A6.

The drain discharge under conditions of perfect overflow through side spill-weirs of DEC was calculated by adopting the Oki's formula [The Japan Society of Civil Engineers 1971]. Water level was observed three times a day both upstream of DEC and inside the DEC chamber. However, the drainage discharge can not be observed when the front orifice gate of DEC is open.

In this study, it is assumed that the drain discharge through DEC consists of the runoff and seepage from the area served.

2.4 Water requirement

In low and flat paddy land such as the Muda area, it is very difficult to measure surface flow because of extremely low hydraulic gradient. Accordingly, the variation of TEW in fields (VS) was measured and the following equation was adopted:-

$$IR + RF = VS + ET + DR \quad \cdots\cdots\cdots \quad (IV\text{-}2)$$

Where IR : irrigation supply
RF : rainfall
VS : variation of TEW in fields
ET : evapotranspiration
DR : drainage including seepage and percolation
$DR = RO + S + P$
(Percolation = outflow of groundwater − inflow of groundwater)

Out of the 5 factors composing the above equation, the irrigation supply (IR), rainfall (RF), and variation of TEW in fields (VS) were obtained by direct measurement. Evapotranspiration (ET) was calculated by multiplying the compound ET ratio by the pan-evaporation (Ep). Drainage including seepage and percolation (DR) is the only factor unknown in the above equation. Therefore DR can be calculated by Eq. (IV-2).

1) Total water requirement

Considering only the period in which water is required for paddy cultivation including the presaturation and supplementary periods, the water balance for the five cropping seasons (3 dry seasons and 2 wet seasons) is shown in Table IV-2.

Based on this table, the average annual consumptive use of water for paddy cultivation was 2,813mm, of which 1,567mm or 55.7% accounted for ET and 1,246mm or 44.3% for DR. On the other hand, the average annual water supply was 2,777mm, of which 908mm or 32.7% was supplied by irrigation and 1,869mm or 67.3% by rainfall. The deficit of 36mm between supply and consumption was accounted for by TEW.

The designed net irrigation requirement is 582mm for two crops in a normal year as quoted in the Muda I feasibility report [Sir William Halcrow & Partners 1964]. As compared with the designed net irrigation requirement, the observed quantity of

Table IV—2 Water balance for double cropping in ISA A, SCRBD 5b, Muda Scheme, Malaysia.

Season	Duration	(days)	(Supply) IR	RF	Total	(Consumption) ET	VS	DR
1984 dry		(184)	562	1,331	1,893	930	17	946
Presaturation	1 Mar. — 7 Apr.	(38)	349	136	485	149	163	173
Supplementary	8 Apr. — 30 Apr.	(23)	32	365	397	117	− 33	312
Growth stage	1 May. — 31 Aug.	(123)	181	830	1,011	664	−113	461
1984 wet		(152)	378	522	900	813	−103	190
Presaturation and Supplementary	16 Sep. — 14 Oct.	(29)	120	94	214	141	18	55
Growth stage	15 Oct. — 14 Feb.	(123)	258	428	686	672	−121	135
1985 dry		(181)	623	1,082	1,705	803	78	824
Presaturation	1 Mar. — 16 Mar.	(16)	81	199	280	69	138	73
Supplementary	17 Mar. — 7 Apr.	(22)	165	37	202	142	− 36	96
Growth stage	8 Apr. — 27 Aug.	(143)	377	846	1,223	592	− 24	655
1985 wet		(153)	329	726	1,055	635	− 79	499
Presaturation and Supplementary	12 Sep. — 7 Oct.	(26)	23	236	259	99	57	103
Growth stage	8 Oct. — 11 Feb.	(127)	306	490	796	536	−136	396
1986 dry		(165)	478	1,322	1,800	795	71	934
Presaturation	15 Mar. — 2 Apr.	(19)	174	178	352	54	128	170
Supplementary	3 Apr. — 20 Apr.	(18)	1	135	136	104	16	16
Growth stage	21 Apr. — 26 Aug.	(128)	303	1,009	1,312	637	− 73	748
Average of dry season		(177)	554	1,245	1,799	843	55	901
Presaturation		(25)	201	171	372	91	142	139
Supplementary		(21)	66	179	245	121	− 17	141
Growth stage		(131)	287	895	1,182	631	− 70	621
Average of wet season		(153)	354	624	978	724	− 91	345
Presaturation and Supplementary		(28)	72	165	237	120	38	79
Growth stage		(125)	282	459	741	604	−129	266
Total for two seasons		(330)	908	1,869	2,777	1,567	− 36	1,246
Presaturation and Supplementary		(74)	339	515	854	332	163	359
Growth stage		(256)	569	1,354	1,923	1,235	−199	887

Notes:

Presaturation period: Period between onset of irrigation and the day when presaturation reaches 100%.

Supplementary period: Period between the day when presaturation reaches 100% and the day when 50% of direct sowing is completed.

Paddy growth stage: Period between the day when 50% of direct sowing is completed and 15 days before 90% of harvesting is completed.

IR : Irrigation supply
RF : Rainfall
ET : Evapotranspiration
VS : Variation of total existing water in fields
DR : Drainage including seepage and percolation

water irrigated was about 60% higher than that in spite of an amount of rainfall 10% higher than in the normal year. The quantity of water irrigated was especially high during the growth stages for both season crops namely, 287mm for the dry season (off-season or first-season) crop and 282mm for the wet season (main season or second-season) crop, in contrast with the designed requirement, i.e. 124mm for the dry season crop and 121mm for the wet season crop [Sir William Halcrow & Partners 1964]. Such high values of the irrigation supply during the growth stages are due to the ineffective use of rainfall for the dry season crop, and the shift of the growth stage of the wet season crop into the dry season. This shift is due to the use of varieties with a long growth period of 125～135 days and the delay of field activities, such as land preparation, transplanting and direct sowing, for the past dry season crop, in spite of the comparatively rapid completion of the presaturation.

The daily consumptive use of water during the paddy growth stage averaged 9.5mm/d for the dry season crop and 6.9mm/d for the wet season crop. In the dry season crop, ET and DR reached a value of 4.8mm/d and 4.7mm/d respectively. In the wet season crop, ET was 4.8mm/d and DR was 2.1mm/d. According to the Muda II feasibility report, consumptive use of water was designed to be 8.6mm/d for the dry season crop and 6.7mm/d for the wet season crop [MADA 1977]. Namely, the actual consumptive use of water was 10% higher in the dry season crop and 3% higher in the wet season crop than the designed consumptive use.

The relationship between water supply and variation of TEW during the supplementary supply and paddy growth periods was analyzed by using the data of the 1984 dry season crop on a daily basis. The following multiple regression equation of which the multiple regression coefficient was 0.930 was derived.

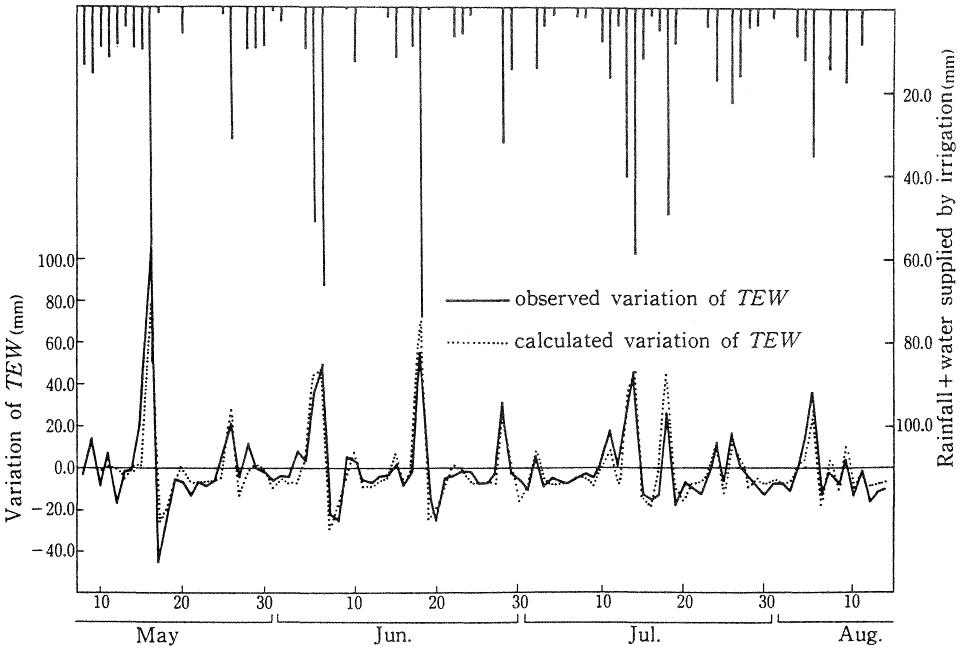


Fig. IV—3 Comparison between observed and calculated variation of TEW (ISA A, SCRBD 5b, 1984 dry season crop), Muda Scheme Malaysia.

$$VS(t) = -6.338+1.029X(t)-0.223X(t-1)-0.157X(t-2) \quad \cdots\cdots (IV-3)$$

where VS(t) : variation of TEW on day t (mm)

X(t) : water supply on day t (mm)

Based on Eq.(IV-3), the movement of water supplied in paddy fields can be analyzed very precisely. The first constant term on the right hand side of the equation refers to the sum of ET and percolation (P). Based on the water balance study carried out in the 1984 dry season, the average daily ET was 5.4mm during the supplementary and paddy growth periods. Therefore, the remainder 0.9mm between the constant 6.3mm of Eq.(IV-3) and the average daily ET 5.4mm can be regarded as the average daily P during the periods.

The second term refers to the direct increment of TEW during the day in relation to the water supply on the same day. The third and fourth terms refer to the decrease of TEW during the day by surface runoff and seepage of the water supplied on the previous day and two days before, respectively. Fig. IV-3 shows a comparison between the observed daily variation of TEW and the calculated variation of TEW by using Eq. (IV-3) as well as the relationship between water supply and variation of TEW.

2) Presaturation requirement

a) Coefficients of effectiveness for irrigation and rainfall during the presaturation period

In order to determine the presaturation requirement for the Muda II area, the coefficients of effectiveness for irrigation and rainfall were analyzed based on the three-year water balance study. In this report, ET and deep percolation (P) are considered as unavoidable losses and included in the effectively used water as well as the increment of TEW. The unavoidable part of seepage also should be included in the amount of effectively used water. However, it is practically impossible to divide seepage into two parts, i.e. unavoidable seepage and avoidable seepage. Therefore, in this paper, the unavoidable seepage was deducted from the amount of effectively used water.

The coefficient of effectiveness for the total amount of water supplied (Efw) at the ISA level is expressed as follows:-

$$Efw = \frac{\triangle TEW+ET+P}{IR+RF} \quad \cdots\cdots (IV-4)$$

where Efw : coefficient of effectiveness for total amount of water supplied

△TEW : increment of TEW

P : percolation (estimated at 0.9mm/d)

Efw changes with the number of days (n) from the onset of presaturation as shown in Fig.IV-4, and a linear relationship was obtained as follows:-

$$\begin{aligned} Efw &= 1.0 && (\text{when } n<5) \\ Efw &= 1.07-0.0153n && (\text{when } 5\leqq n<22) \quad \cdots\cdots (IV-5) \\ Efw &= 0.77-0.0014n && (\text{when } 22\leqq n<40) \end{aligned}$$

Where n : number of days from the onset of presaturation

(Efw is evaluated cumulatively from day 1)

Moreover, the other analysis based on Eq. (IV-13) which will be described later revealed that the coefficients of effectiveness for IR and RF are almost of the same order (approximately 0.72 each) during the presaturation period. Accordingly, the following equation was derived.

$$Efi\cdot IR+Efr\cdot RF = \triangle TEW+ET+P \quad \cdots\cdots (IV-6)$$

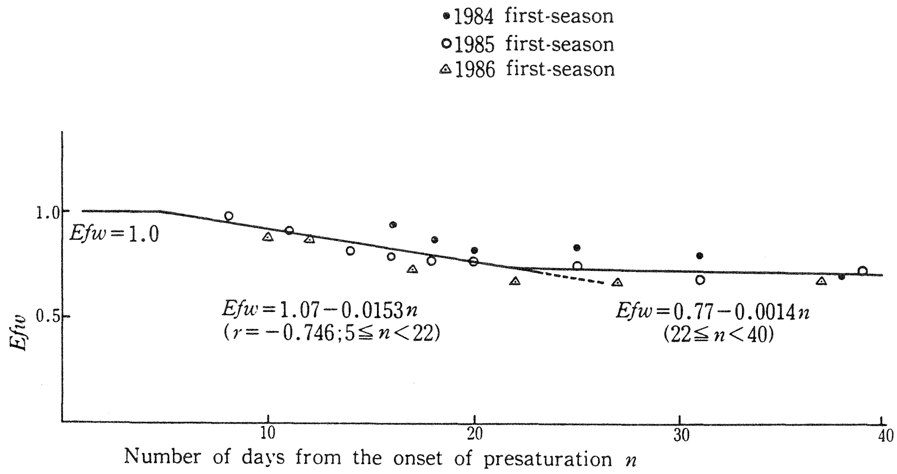


Fig.IV—4 **Changes in the coefficient of effectiveness for the total amount of water supplied (Efw) during the presaturation period in ISA A, SCRBD 5b, Muda Scheme, Malaysia.**

where Efi : coefficient of effectiveness for irrigation
Efr : coefficient of effectiveness for rainfall
Efi ≒ Efr ≒ Efw

It should be noted that the coefficients of effectiveness for irrigation (Efi), rainfall (Efr) and the total amount of water supplied (Efw) may be interpreted as measures of the efficiencies of usage respectively.

b) Presaturation requirement

By modifying Eq. (IV-4), the presaturation requirement can be expressed as follows:-

$$PR = \frac{\triangle TEW + ET + P}{Efw} \quad \cdots\cdots (IV\text{-}7)$$

where PR: presaturation requirement

For the practical use of Eq. (IV-7), it is necessary to set up the target presaturation period and △TEW at first. Then, Efw can be calculated by Eq. (IV-5) and ET+P for the given period should be estimated.

For example, when TEW is increased by 160mm, i.e. 85mm for the soaking of soil and 75mm for the ponding depth, within 35 days, the presaturation requirement is calculated as follows:-

ET= 5.5mm/day × 35 days = 192.5mm
P= 0.9mm/day × 35 days = 31.5mm
△TEW= 160.0mm
Efw= 0.77 - 0.0014 × 35 = 0.72

Accordingly,

$$PR = \frac{160.0+192.5+31.5}{0.72} = 533\text{mm}$$

Assuming that daily ET and P are constant during the presaturation period, the change of presaturation requirement with the change of conditions, such as the target presaturation period and $\triangle$TEW, can be tabulated for practical use.

Then, another analysis was carried out so as to determine the coefficients of effectiveness for IR and RF in relation to the increment of TEW. This analysis was based on the assumption that the following theoretical linear relationship is valid.

$$\alpha\ \mathrm{IR} + \beta\ \mathrm{RF} = \triangle \mathrm{TEW} \qquad \cdots\cdots (\mathrm{IV\text{-}8})$$

where α : coefficient of effectiveness for IR to $\triangle$TEW

β : coefficient of effectiveness for RF to $\triangle$TEW

By substituting the values of cumulative IR, RF and $\triangle$TEW when 100% of the study area was presaturated in three seasons for Eq. (IV-8), the following equations were obtained.

$$\begin{aligned} 349.3\alpha + 135.7\beta &= 170.6 \ (\text{1984 dry season}) \\ 81.4\alpha + 198.5\beta &= 137.9 \ (\text{1985 dry season}) \qquad \cdots\cdots (\mathrm{IV\text{-}9}) \\ 174.3\alpha + 177.8\beta &= 144.3 \ (\text{1986 dry season}) \end{aligned}$$

The optimum solutions of α and β were obtained by the method of least square as follows:-

$$\alpha = 0.261$$
$$\beta = 0.576$$

Therefore, the following relationship was derived.

$$0.261\ \mathrm{IR} + 0.576\ \mathrm{RF} = \triangle \mathrm{TEW} \qquad \cdots\cdots (\mathrm{IV\text{-}10})$$

In Eq. (IV-10), it is notable that the coefficient of effectiveness for IR to $\triangle$TEW is far smaller than that for RF in contrast with those for IR and RF in relation to the amount of effectively used water (EUW=$\triangle$TEW+ET+P) of the same order, as expressed by Eqs. (IV-5) and (IV-6). The approximate coefficients of effectiveness for IR and RF when 100% of the area was presaturated were 0.72 each. Therefore, the difference between Eq. (IV-6) and Eq. (IV-10) can be written as follows:-

$$0.46\ \mathrm{IR} + 0.14\ \mathrm{RF} = \mathrm{ET} + \mathrm{P} \qquad \cdots\cdots (\mathrm{IV\text{-}11})$$

The reason why the coefficient of effectiveness for IR in relation to $\triangle$TEW is very low compared with that or RF is expressed by this equation very well. Namely, IR tends to be consumed not for $\triangle$TEW but for ET and P. On the other hand, RF tends to work effectively for $\triangle$TEW instead of ET and P, due to the characteristics of these parameters. As IR is conveyed and distributed to the paddy fields gradually and constantly with a certain time lag, it is easily consumed by ET and P before contributing to the increment of TEW.

As RF is brought directly to the paddy fields without any time lag, it plays a significant role in the rapid increment of TEW during the presaturation period.

Though, Eq. (IV-10) does not include a time factor, it can be applied as a convenient method for the estimation of the presaturation requirement for a normal presaturation supply. Eq. (IV-10) can be presented as shown in Fig.IV-5.

For the approximate estimation of initial TEW before the onset of the presaturation supply, the following equation derived from the observed data can be applied (Fig.IV-6).

$$\begin{aligned} \mathrm{TEW}_0 &= 1.05 \sum_{i=1}^{30} \left(\frac{31-i}{30} R(t\text{-}i)\right) - 18.4 \\ &= 1.05\ \bar{R} - 18.4 \qquad (\mathrm{TEW}_0 \geqq 0) \qquad \cdots\cdots (\mathrm{IV\text{-}12}) \end{aligned}$$

where TEW_0 : initial TEW

i : number of days before the beginning of presaturation

$R(t\text{-}i)$: rainfall on the day corresponding to i days before the onset of presaturation

$\bar{R}$: weighted rainfall for 30 days

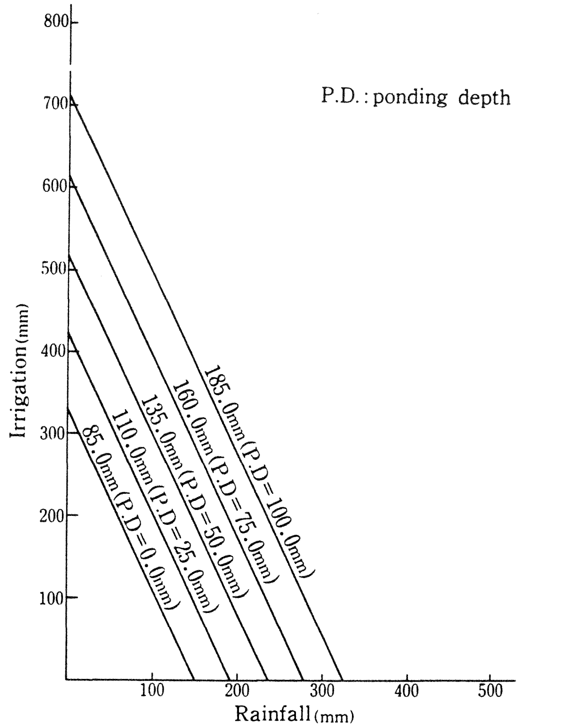


Fig. IV—5 Presaturation requirement for Muda II block, Muda Scheme, Malaysia.

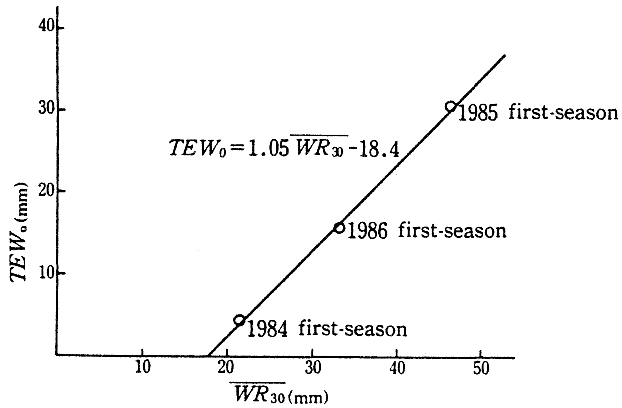


Fig. IV—6 Relationship between initial value of TEW and weighted rainfall for 30 days before the onset of presaturation, Muda Scheme, Malaysia.

Even though the value of the coefficient of effectiveness for IR in relation to △TEW is only 0.261, the efficiency was improved by the tertiary canal. According to S. Yashima, the relative efficiency of IR against RF was only 25% under the Muda I conditions [1984].

In this study, the relative efficiency of IR against RF was 45%. Thus, the increment of relative efficiency can be considered to be associated with the tertiary development.

3) Coefficients of effectiveness for irrigation and rainfall during the paddy growth stage of the dry season crop

In order to determine the coefficients of effectiveness for IR and RF during the paddy growth stage of the dry season, monthly data were used for the analysis which is similar to that presented in the previous paragraph based on the following linear relationship.

$$Efi \cdot IR + Efr \cdot RF = \triangle TEW + ET + P \quad \cdots\cdots\cdots (IV\text{-}13)$$

where Efi : coefficient of effectiveness for irrigation during the paddy growth stage

Efr : coefficient of effectiveness for rainfall during the paddy growth stage

IR, RF, $\triangle$TEW, ET and P are given on a monthly basis.

In fact, it is very difficult to represent the coefficients of effectiveness for IR and RF by a linear equation, because heavy rainfall, which does not contribute linearly to the increment of effectively used water (EUW) in paddy fields, is very common during this stage compared with the presaturation period. Therefore, to overcome this difficulty, the upper limit of monthly effective rainfall was considered.

At first, out of 8 sets of data, 5 sets for which monthly rainfall was not very high were selected for the analysis. Then Efi and Efr were evaluated by the method of least square. Based on the value of Efi and Efr, the upper limit of effective rainfall which gives a good agreement with the actual effectively used water was obtained. Finally, the following relationship was derived from the observed data on a monthly basis.

$$0.457IR + 0.688RF = ET + \triangle TEW + P \quad \cdots\cdots\cdots (IV\text{-}14)$$

By assigning the value of Efi and Efr to the eight sets of data and comparing the actual value of EUW and the estimated one, it was found that the following conditions should be attached to the above equation.

(i) When monthly IR is less than or equal to 40mm, Efi is 1.0. When monthly IR is larger than 40mm and less than 88mm, Efi·IR is 40mm.

(ii) The maximum value of Efr·RF is 150mm, that is when monthly RF exceeds 218mm, the effective rainfall is 150mm.

Under the above-mentioned conditions, the relationship between actual EUW and estimated EUW is shown in Fig.IV-7.

Namely, the coefficients of effectiveness for irrigation (Efi) and rainfall (Efr) can be presented as follows:-

$$\begin{aligned}
Efi &= 0.457 && (\text{when } IR \geqq 88) \\
&= 0.457 \sim 1.0 && (Efi \cdot IR = 40, \text{ when } 40 < IR < 88) \\
&= 1.0 && (\text{when } IR \leqq 40) \\
Efr &= 0.688 && (\text{when } RF \leqq 218) \\
&= 0.333 \sim 0.688 && (Efr \cdot RF = 150, \text{ when } 218 < RF < 450)
\end{aligned}$$

2.5 Runoff characteristics

In order to clarify the characteristics of runoff (including seepage flowing into drain) in a tertiary development area during the growing period of rice plants, the area of 48.0ha which accounts for the greater part of the right bank of the tertiary

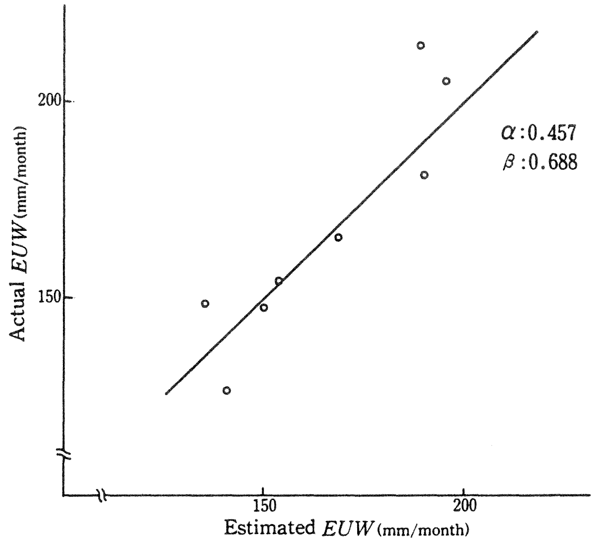


Fig. IV—7 Relationship between actual and estimated EUW, Muda Scheme, Malaysia.

canal and is served by the DEC of the tertiary drain SD1/R2C was selected. The multiple regression model method was adopted for the analysis. Under the assumption that there is no time lag between IR and RF, the following multiple regression equation was derived.

$$Y(t) = 0.338 + 0.012X(t) + 0.202X(t-1) + 0.117X(t-2) + 0.091X(t-3) + 0.056X(t-4) + 0.025X(t-5) + 0.030X(t-6) + 0.024X(t-7) \quad \cdots\cdots (IV\text{-}15)$$

where $Y(t)$: estimated runoff on day t (mm)

$X(t-i)$: total water supply on day t-i (mm)

$X(t-i) = IR(t-i) + RF(T-i) \quad (i=0,1,\ldots 7)$

The value of the multiple correlation coefficient of the equation was 0.713. The statistical unit hydrograph for the growing period of rice plants is shown in Fig. IV-8. It is obvious from the hydrograph that the water supply of the previous day exerts an influence on the runoff of the day. The water supply of the day does not affect appreciably the runoff of the day. Fig. IV-9 shows the comparison between observed runoff and calculated runoff by Eq. (IV-15) as well as the relationship between water supply and runoff.

In a strict sense, it is necessary to consider the time lag of irrigation supply for the analysis, because it takes time for irrigation water to reach the paddy lots through the levees in contrast to rainfall which is brought to the paddy lots immediately and evenly. Thus, an analysis considering the time lag between IR and RF was carried out for trial. The following multiple regression model of which the multiple correlation coefficient is 0.747 was obtained.

$$Y(t) = 0.177 + 0.081X(t) + 0.204X(t-1) + 0.122X(t-2) + 0.086X(t-3) + 0.035X(t-4) + 0.008X(t-5) + 0.017X(t-6) + 0.012X(t-7) + 0.017X(t-8) \quad \cdots\cdots (IV\text{-}16)$$

where $Y(t)$: estimated runoff on day t (mm)

$X(t-i) = IR(t-i-5) + RF(t-i)$ (mm)

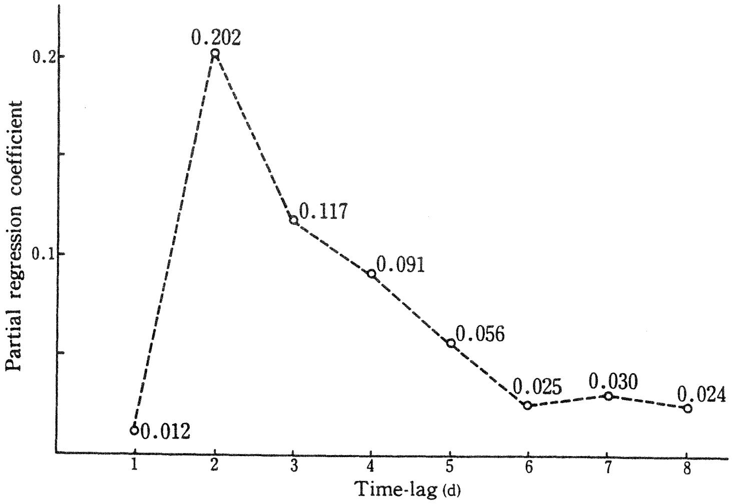


Fig. IV—8 **Statistical unit hydrograph (SD1/R2C of ISA A, SCRBD 5b), Muda Scheme, Malaysia.**

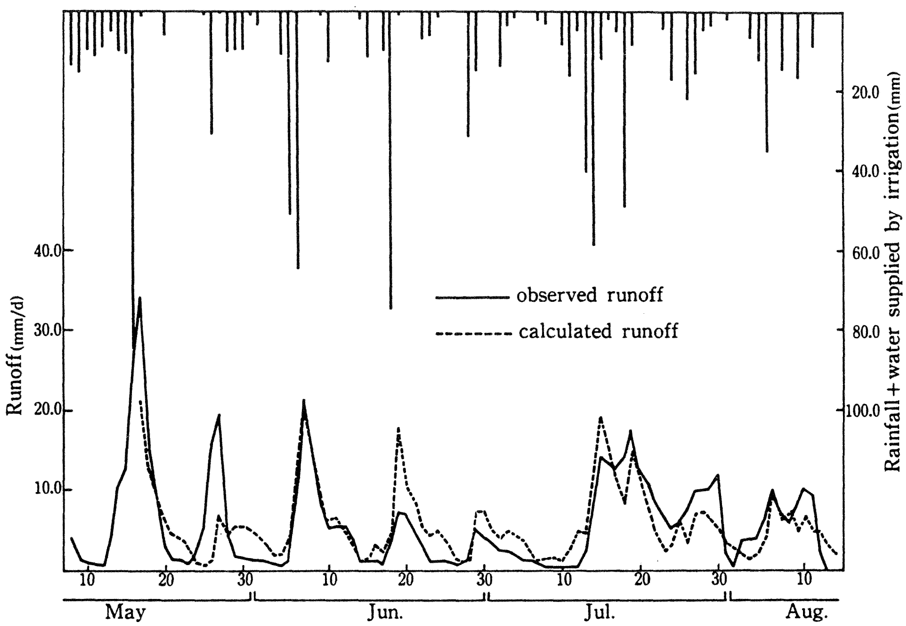


Fig. IV—9 **Comparison between observed runoff and calculated runoff (SD1/R2C of ISA A, SCRBD 5b), Muda Scheme, Malaysia.**

Based on this model, the time lag between IR and RF is 5 days. Judging from the actual conditions of the study area, the obtained time lag seems rather long. Therefore, further analysis should be carried out to confirm this value.

2.6 Findings and conclusions

Based on the case study on the mechanism of water consumption and water requirement in the Muda area of Malaysia, the following findings and conclusions were obtained:-

1) The average annual consumptive use of water for paddy cultivation was 2,813mm, of which 1,567mm (55.7%) was consumed by evapotranspiration and 1,246mm (44.3%) by drainage including seepage and percolation. The observed quantity of water irrigated for two crops was about 60% higher than that of the designed net irrigation requirement for two crops in spite of an amount of rainfall 10% higher than in the normal year. Such a high value of the irrigation supply is due to the ineffective use of rainfall for the dry season crop and the shift of the growth stage of the wet season crop into the dry season due to the use of varieties with a long growth period of 125~135 days and the considerable delay in field activities, such as land preparation, transplanting and direct sowing. Good farm management based on the suitable cropping schedule summarized in Appendix II is essential for the successful water management in the tertiary system (See Appendix II).

2) The relationship between the water supply and variations of the ponding depth was analyzed, and equation (IV-3) was obtained to express the movement of water supplied to the tertiary development area. From the equation, the average daily percolation during the supplementary and paddy growth periods was estimated at 0.9mm/d.

3) Coefficient of effectiveness for irrigation and rainfall in the tertiary development area is almost of the same order (around 0.72) during the presaturation period, and can be expressed by a linear equation (IV-5).

However, the coefficient of effectiveness for irrigation in relation to presaturation is 0.261 and differs very much from that of rainfall (0.576), because irrigation water tends to be consumed for evaporation and percolation, and not for presaturation.

On the other hand, rainfall tends to work effectively for the presaturation instead of evaporation and percolation. By using these coefficients of effectiveness, a convenient method for the estimation of the presaturation requirement was devised.

4) The increment of relative efficiency of IR against RF from 25% under the Muda I conditions to 45% under the Muda II conditions can be ascribed to the effect of tertiary development.

5) The equation (IV-12) derived from the observed data is applicable for the approximate estimation of initial TEW before the onset of the presaturation supply.

6) Coefficient of effectiveness for IR is 0.457 and that for RF is 0.688 in the tertiary development area during the paddy growth stage of the dry season crop.

7) Statistical unit hydrograph models were developed for the estimation of runoff including seepage flowing into drain in the tertiary development area.

3. Case study in the dry zone area, Sri Lanka

3.1 Study areas

For this study, the Rajangana and Nachchaduwa Schemes which are classified as major irrigation works located in the northern dry zone were selected. The locations of these schemes are shown in Fig.III-7. The Rajangana Scheme which receives water from two tanks, i.e. the Rajangana Tank with a storage capacity of 100×10^6m^3 and the Angamuwa Tank with a storage capacity of 14×10^6m^3, covers 7,100ha (paddy land: 5,500ha, upland: 1,600ha). This area is included in the System H of the Mahaweli Development Scheme and rice double cropping has been practiced since 1976. The Nachchaduwa Scheme covering 2,200ha of paddy land receives water from the Nachchaduwa Tank with a storage capacity of $56 \times 10^6 m^3$. Since the area is also included in the System H of the Mahaweli Development Scheme, rice double cropping prevails in the area.

(Detailed study lot in Rajangana Scheme)

In order to investigate the mechanism of water consumption in a terminal paddy lot, Lot No.219 of Tract 2 on L.B of Rajangana Scheme was selected for detailed study. The lot, covering a surface of 0.7ha, is made up of 52 plots where a plot-to-plot irrigation system has been adopted. The average slope between the inlet and the outlet of the lot is about 1 in 63. The location of the detailed study lot is shown in Fig.IV-10 together with the related canal system. The canal density of this scheme is estimated at around 45 to 50m/ha.

(Study area in Nachchaduwa Scheme)

For the study on the mechanism of water consumption and irrigation requirement in paddy fields extending over a large area, the Nachchaduwa Scheme was selected. Irrigation water is fed to the paddy fields by two main channels, i.e. the High Level Main Channel and the Low Level Main Channel. These two main channels run parallel to each other on the sloping topography. Moreover, the Low Level Main Channel runs roughly parallel to the Malwatu Oya (River), which is utilized as drainage channel. The research area covers 786.1ha of which 155.6ha receive water from the High Level Main Channel and the remaining 630.5ha receive water from the Low Level Main Channel. Fig.IV-11 shows the outline of the irrigation system in the study area.

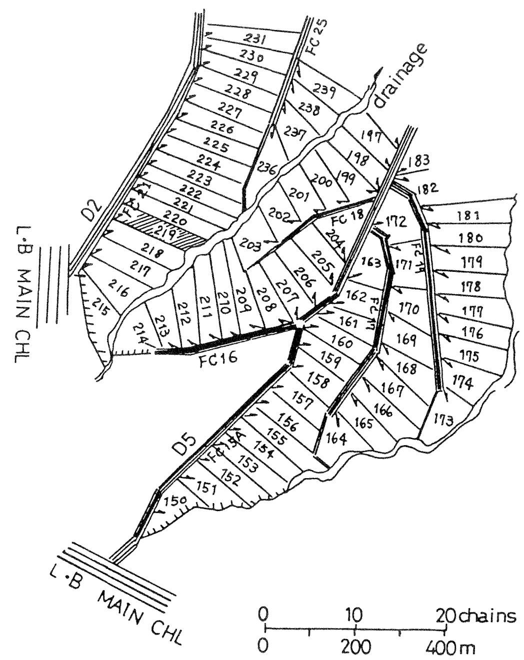


Fig.IV—10 Location of detailed study lot (Lot No.219) in L.B Tract 2, Rajangana Scheme, Sri Lanka.

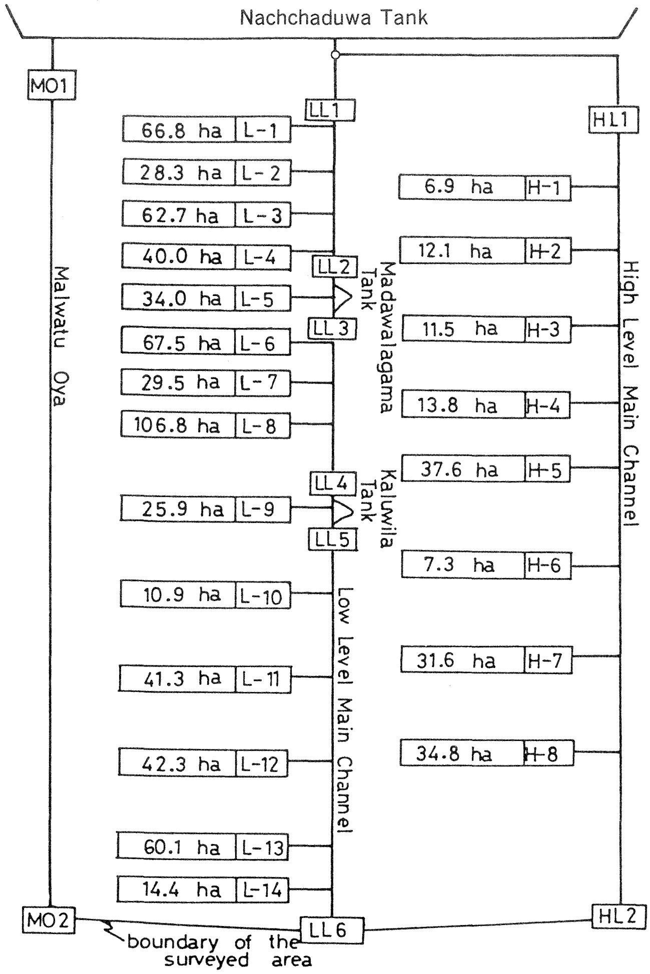


Fig. IV—11 Outline of the irrigation system in the surveyed area, Nachchaduwa Scheme, Sri Lanka.

3.2 Evapotranspiration (ET)

ET was observed for 5 cropping seasons (1977/78 Maha season~1979/80 Maha season) by using lysimeters. Pan-evaporation was observed at two points, i.e. the detailed study lot and the meteorological enclosure in the engineer's office for the Rajangana Scheme, by using 'class A' pans. Some difference was noted in the observed Ep values between the two points. Namely, the value of Ep observed in the detailed study lot was slightly smaller than that in the meteorological enclosure because the micrometeorological conditions are normally milder in the paddy field area than in the meteorological enclosure. Generally, Ep is continuously observed in the meteorological enclosures on a daily basis extending over a long period of time. Accordingly, it is more practical and convenient for the investigation of the ET/Ep ratio to adopt the Ep observed in the meteorological enclosure. In this study Ep observed in the meteorological enclosure was adopted. The results are presented as follows:-

i) ET increased with the growth of the paddy plant, and gradually decreased after the peak at heading stage. The stage of plant growth rather than Ep shows the highest correlation with ET in contrast with the changes of ET which in Japan tend to depend on the weather conditions instead of the stage of plant growth. The multiple correlations observed between ET which can be predicted and Ep, stage of plant growth, and rainfall which are variables, are high; the following multiple regression equations were obtained both in the Maha and Yala seasons, respectively.

(Maha season)

$$ET=6.08+0.284Ep-0.0845Sh_2+0.0545Sh_1 \quad \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots (IV\text{-}17)$$

(Yala season)

$$ET=3.59+0.0534Sb-0.165RF+0.079Ep-0.017Sh_1 \quad \cdots\cdots\cdots\cdots (IV\text{-}18)$$

where ET : evapotranspiration (mm/d)

Ep : pan-evaporation (mm/d)

Sb : number of days elapsed after broadcasting

Sh_1 : number of days elapsed after heading time (before heading; $Sh_1=0$)

Sh_2 : number of days after and before heading time ($Sh_2 \geqq 0$)

Table IV—3 Planning figures for evapotranspiration, dry zone area of Sri Lanka.

(mm)

Season	Growth 0—10	10—20	20—30	Stage 30—40	40—50	50—60	(days) 60—70	70—80	80—90	Average
Maha Season	3.0	3.7	4.9	5.8	6.9	8.3	8.2	7.6	7.3	6.2
	(3.0)	(3.7)	(4.9)	(5.3)	(6.0)	(7.3)	(7.3)	(7.2)	(7.1)	(5.8)
Yala season	5.0	5.0	6.0	6.0	8.6	9.2	9.4	8.3	8.3	7.3
	(5.0)	(5.0)	(5.8)	(5.8)	(7.5)	(7.6)	(8.0)	(7.7)	(7.7)	(6.7)

Notes: Growth stage in terms of number of days elapsed from broadcasting.
Upper line……maximum evapotranspiration
Lower line……mean evapotranspiration

Table IV—4 Planning figures for ET/Ep ratio, dry zone area of Sri Lanka.

Season	Growth 0—10	10—20	20—30	Stage 30—40	40—50	50—60	(days) 60—70	70—80	80—90	Average
Maha season	1.0	1.1	1.3	1.5	1.6	2.0	1.8	1.8	1.8	1.54
	(1.0)	(1.1)	(1.2)	(1.4)	(1.6)	(1.8)	(1.7)	(1.7)	(1.7)	(1.47)
Yala season	1.0	1.0	1.0	1.3	1.7	1.9	1.7	1.7	1.7	1.44
	(1.0)	(1.0)	(1.0)	(1.1)	(1.5)	(1.5)	(1.4)	(1.4)	(1.4)	(1.26)

Notes: Growth stage in terms of number of days elapsed from broadcasting
Upper line……maximum ET/Ep ratio
Lower line……mean ET/Ep ratio

RF : daily rainfall (mm/d)

ii) Values of ET suited to each growing period of 10-day which must be estimated when planning irrigation both in the Maha and Yala seasons were obtained as shown in Table IV-3. Similarly, as mentioned above, the optimum ratio between ET and Ep for the planning of the irrigation schemes could be obtained as shown in Table IV-4.

3.3 Percolation (P) and seepage (S)

(1) Physical characteristics of paddy soil

Based on the particle size analysis of the paddy soil in the detailed study lot, the soil texture was classified as SCL (sandy clay loam) by the USDA system. The soil contained 57~68% sand, 10~12% silt and 20~31% clay. The apparent-specific gravity of the soil ranged from 1.5 to 1.8 and the solid phase occupied 56 to 66%, namely its compactness seemed to be comparatively high. As the coefficient of water conductivity ranged from 10^{-5} to 10^{-4}cm/s in the plow layer and hard pan, and 10^{-4} to 10^{-3}cm/s in the subsoil, respectively, the soil seemed to be comparatively permeable.

(2) Percolation and seepage

Here, the percolation (P) was observed together with the seepage (S) by adopting the water balance method in the detailed study lot. The 'N-type measuring apparatus for water requirement' and 'quick percolation measuring apparatus' were jointly used with the water balance method for the investigation.

Table IV-5 shows the water balance for the 1979 Yala season and 1979/80 Maha season crops in the detailed study lot. Dyke-leakage was also observed partially in the study lot. The results are presented as follows:-

Table IV—5 Water balance in the detailed study lot, Rajangana Scheme, Sri Lanka.

Unit: mm (%)

Season	Duration (days)	(Supply		)	(Consumption			)
		IR	RF	Total	ET	P+S	RO	PR
1979 Yala season	102	4087 (97.9)	88 (2.1)	4175 (100.0)	593 (14.2)	2632 (63.0)	792 (19.0)	157 (3.8)
Presaturation	24	1276 (99.5)	6 (0.5)	1282 (100.0)	86 (6.7)	728 (56.8)	311 (24.3)	157 (12.2)
Growth stage	78	2811 (97.2)	82 (2.8)	2893 (100.0)	507 (17.5)	1904 (65.8)	481 (16.7)	- (-)
1979/80 Maha season	125	5253 (92.6)	417 (7.4)	5670 (100.0)	634 (11.2)	2873 (50.7)	2140 (37.7)	23 (0.4)
Presaturation	44	1990 (83.7)	388 (16.3)	2378 (100.0)	99 (4.2)	1390 (58.4)	866 (36.4)	23 (1.0)
Growth stage	81	3263 (99.1)	29 (0.9)	3292 (100.0)	535 (16.3)	1483 (45.0)	1274 (38.7)	- (-)

Notes ; IR : Irrigation supply
RF : Rainfall
ET : Evapotranspiration
P+S: Percolation and seepage
RO : Surface runoff
PR : Presaturation requirement

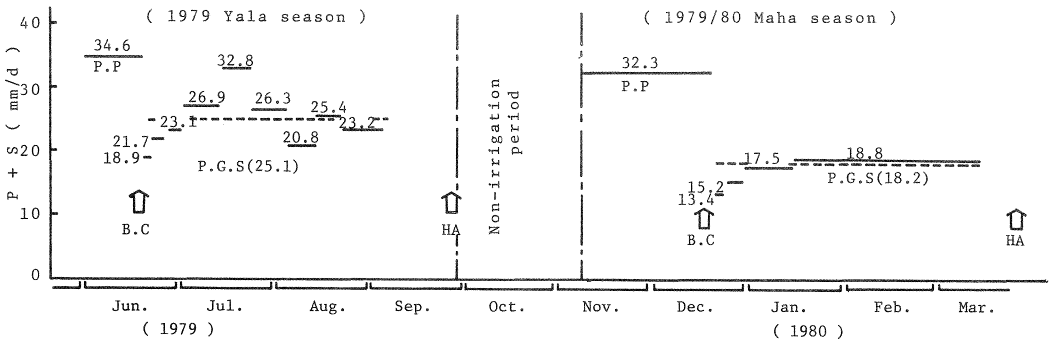


Fig.IV—12 Fluctuation of (P+S) in the detailed study lot, Rajangana Scheme, Sri Lanka.

i) The amount of (P+S) shows a wide range of fluctuations during the irrigation period. Especially, it was interesting to note that there was a sudden reduction in the amount of (P+S) immediately after puddling. It is, therefore, evident that the puddling operation strongly affects (P+S). After puddling, (P+S) tended to increase gradually throughout the plant growth period due to the development of small cracks in the surface soil through the soil drying process (Fig.IV-12).

ii) The superficial layers of soil determine the amount of (P+S). Therefore, in taking into account this factor as well as what had been mentioned in i), the effect of puddling appears to be significant.

iii) Percolation of water follows a saturation pattern.

iv) The amount of (P+S) averaged about 20mm/d (Fig.IV-12).

v) The amount of (P+S) in the Yala season was higher than this value in the Maha season presumably due to the following two reasons.

① The formation of cracks in the soil during the non-irrigation period before the Yala season is more pronounced than during the non-irrigation period before the Maha season due to the difference in the weather conditions between the two periods.

② Intermittent irrigation is frequently practised in the Yala season due to the insufficiency in irrigation water compared with the Maha season. As a result, the surface soil is easily exposed to the sun and cracks occur in the Yala season compared with the Maha season.

vi) The average amount of (P+S) in the lot was markedly influenced by the presence of fissures, cracks, and holes which were caused by soil insects and roots. Especially, since the subsoil is never broken up and dispersed by puddling, the fissures, cracks and holes formed in the subsoil persist for a long time and frequently adversely affect the mechanism of percolation and seepage.

vii) Dyke-leakage: The ratio of unit dyke-leakage (l/m/d) to (P+S) (mm/d) ranges from 1.6 to 7.6, with an average of 4.0. In a small plot, covering an area of approximately 60m^2, the quantity of water originating from dyke-leakage exceeds the water requirement in depth, and therefore weighs heavily on the total water movement. Therefore, pronounced dyke-leakage complicates water management in the lot, resulting in an excessive wastage of water. Therefore, the dykes surrounding each plot should be maintained with due attention in order to use the irrigation water as effectively as possible.

(3) Percolation and seepage control methods

From the standpoint of effective water use, it is necessary to devise methods for controlling percolation and seepage. Five methods were evaluated with respect to their effectiveness in the detailed study lot in Rajangana Scheme. It was observed that the application of subsoil compaction, crushing and compaction, and bentonite dressing (both stratifying and mixing) methods reduced percolation and seepage to below 10mm/d. (See Appendix III)

The water balance study carried out in the Dewa huwa Scheme demonstrated the effect of land consolidation on percolation and seepage control. Namely, in the process of implementation of land consolidation, paddy soil is compacted and puddled by heavy machinery resulting in the reduction of percolation (including seepage) and dyke-leakage. The observed percolation was only 2mm/d in the consolidated lot in contrast with 9mm/d in the adjacent non-consolidated lot. (See Appendix IV)

3.4 Presaturation requirement (PR)

Based on the water balance shown in Table IV-5, water consumption during the presaturation period is very high, accounting for more than ten times the presaturation requirement (PR), i.e. the minimum quantity of water required for the presaturation of paddy fields which must be estimated when irrigation is being planned. Such a high water consumption during the presaturation period is due to the delay in field activities, such as land preparation, direct sowing and transplanting. The presaturation requirement as well as the average amount of (P+S) during the presaturation period are closely related to the "weighted rainfall ($\bar{R}$)" for 30 days prior to the onset of presaturation as shown in Fig.IV-13, and can be expressed by the following equations.

$$PR = 285.9 - 1.3\bar{R} \qquad \cdots\cdots (IV\text{-}19)$$

$$P+S = 38.55 - 0.036\bar{R} \qquad \cdots\cdots (IV\text{-}20)$$

where $\bar{R}$: weighted rainfall for 30 days prior to the onset of presaturation (mm)

$$\bar{R} = \sum_{i=1}^{30} \left(\frac{31-i}{30} R(t-i)\right)$$

PR : presaturation requirement (mm)

P+S : average percolation and seepage during the presaturation period (mm/d)

i : number of days before the onset of presaturation

R(t-i) : rainfall on the day corresponding to i days before the onset of presaturation (mm/d)

These equations indicate very precisely that PR and (P+S) are strongly affected by the rainfall conditions before the onset of presaturation.

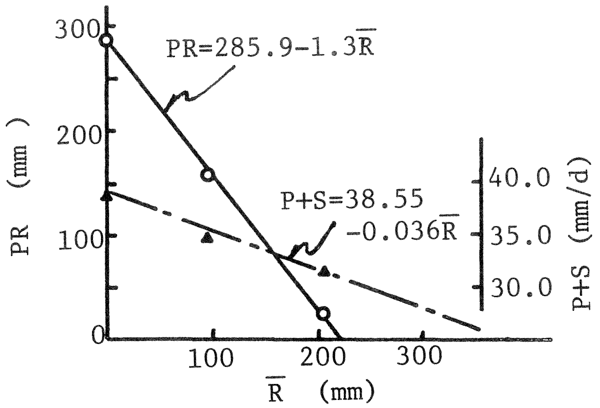


Fig. IV—13 Relationship among $\bar{R}$, PR and (P+S), Rajangana Scheme, Sri Lanka.

3.5 Surface runoff (RO)

The actual surface runoff from paddy fields accounts for a comparatively high percentage of the total water consumption in paddy fields. The average daily runoff accounted for 7.8mm/d or 19% of the average daily water consumption in the 1979 Yala season and 17.1mm/d or 37.7% in the 1979/80 Maha season. The following trends of surface runoff were recognized.

i) Surface runoff is more pronounced in the Maha season than in the Yala season.

ii) Surface runoff is more pronounced during the presaturation period than during the growth period of rice plants. This trend is more conspicuous in the Yala season.

The first trend is ascribed to the large difference in the water conditions between the Maha season and the Yala season. Namely, as water is abundant in the Maha season, surplus water intake prevails. Moreover, farmers frequently continue to introduce water into their fields without controlling the inlet regardless of the amount of rainfall. On the other hand, some measures for water saving such as intermittent irrigation are taken in the Yala season due to the shortage of water.

However, judging from the average daily runoff of 7.8mm/d observed in 1979 Yala season, intermittent irrigation did not appear to be a suitable measure for saving water under the current conditions of terminal fields. When intermittent irrigation is practiced, each lot should substitute its plot-to-plot irrigation method for the ponding irrigation method so as to avoid waste of water. However, it is physically impossible to interrupt the water movement and to substitute plot-to-plot irrigation for ponding irrigation in each plot even though the intermittent irrigation method is adopted. This would result in a considerable surface runoff. In order to promote economical water management in a terminal field, land consolidation should be given priority. (See Appendix IV)

The second trend is caused by the heavy dyke-leakage and rapid water flow on the fields due to the lack of levee coating and puddling during the presaturation period.

3.6 Mechanism of water consumption and irrigation requirement in paddy fields extending over a large area

Based on the short-term water balance study carried out in the Nachchaduwa

Scheme, the following results were obtained.

i) It can be said that the two main channels are very conveniently arranged by making the best use of the topographical characteristics of the area and water can be used effectively. Namely, the drainage water of the higher tracts commanded by the High Level Main Channel accrue to the Low Level Main Channel.

ii) The average percolation and seepage losses were approximately 10mm/d. Eighty-100% of the percolation and seepage water returned to the drainage channel as surface water. Thus repeated use of water is possible in the downstream area.

3.7 Findings and conclusions

Based on the case study on the mechanism of water consumption and water requirement in the dry zone area of Sri Lanka, the following findings and conclusions were obtained:-

1) ET increased with the growth of the paddy plant, and gradually decreased after the peak at heading time. Multiple regression equations (IV-17) and (IV-18) which can predict ET were obtained for the two seasons. Values of ET and ET/Ep suited to each growth period of 10-day which must be estimated when irrigation is planned were obtained (Tables IV-3, IV-4).

2) Based on the water balance studies carried out in the detailed study lot of the Rajangana Scheme and study area of the Nachchaduwa Scheme, the percolation (including seepage) should be estimated at at least 10mm/d in the dry zone area of Sri Lanka. This amount seems reasonable in taking account of the undulating topography and sandy clay loam covering the dry zone area. However, the majority of the irrigation projects under planning and construction in the dry zone area have been conceived under the assumption that percolation and seepage losses amount to 2～4mm/d. It appears that the amount of percolation and seepage losses has been undoubtedly underestimated.

3) Eighty～100% of the percolation and seepage losses returned to the drainage channel as surface water. Thus repeated use of water is possible in the downstream area.

4) In the dry zone of Sri Lanka, such an underestimation of the percolation and seepage losses in the planning of irrigation appears to have originated from the figures obtained by subtracting the quantity of return flow from the amount of percolation and seepage.

4. Comparison between water requirement in the Muda area and dry zone area of Sri Lanka

4.1 Evapotranspiration (ET)

In the Muda area, the ratio of ET to pan-evaporation during the paddy growth stage was determined by K. Sugimoto [1971] and S. Yashima [1984]. K. Sugimoto observed the pan-evaporation (Eps) by using a small pan, 20cm in diameter and 10cm in height, installed at the station near the paddy field. On the other hand, S. Yashima used a large black pan with a diameter of 120cm that had been standardized by the DID for the measurement of the pan-evaporation (Epo). In Japan, the ET ratio (ET/Eps) in different regions was analyzed by S. Nakagawa as shown in Table IV-6 [1966, 1967].

In the meteorological enclosure in the engineer's office for the Rajangana Scheme,

Table IV—6 General tendency of ET ratio in different regions in Japan [Nakagawa, 1966].

Region	May	June	July	August	September	October
Hokkaido		1.1—1.3	1.3—1.4	1.4—1.6		
Tohoku		1.1—1.2	1.2—1.3	1.3—1.4	1.4—1.5	
Kanto		1.3	1.3—1.5	1.4—1.5	1.7	
Hokuriku		0.9—1.0	1.0—1.4	1.5—1.7	1.3	
Tokai		0.8	1.0—1.2	1.2—1.6		
Kinki			0.8—1.2	1.2—1.4	1.5—1.7	
Sanin		1.1	1.1—1.2	1.1—1.2	1.2	
Sanyo			1.2—1.4	1.4—1.6	1.5—1.7	
Shikoku		1.1	1.0—1.2	1.0—1.2	1.1—1.5	
Kyushu			1.0—1.1	1.2—1.4	1.4—1.6	1.5—1.4
Average		0.9—1.2	1.0—1.4	1.1—1.6	1.3—1.7	1.5—1.4
Early-season culture	0.8—1.0	1.1—1.2	1.3—1.5	1.3—1.4		
Late-season culture			0.8	0.9—1.0	1.1—1.4	1.4—1.1

Table IV—7 Comparison of ET and ET/Eps among Muda area (Malaysia), Dry zone area (Sri Lanka) and Japan.

Area	ET		ET/Eps		Remarks
	Dry*)	Wet**)	Dry*)	Wet**)	
Muda area (Malaysia)	Ave. 6.4	Ave. 5.3—5.9	Ave. 1.17	Ave. 1.20	by K. Sugimoto
Dry zone area (Sri Lanka)	5.0—8.0 (Ave. 6.7)	3.0—7.3 (Ave. 5.8)	0.8—1.3 (Ave. 1.0)	0.6—1.3 (Ave. 1.0)	by Y. Kitamura
Japan	3.6 — 6.0 (Ave. 4.9)		0.9 — 1.7 (Ave. 1.3)		by S. Nakagawa

Notes : *) Dry season includes Yala season in Sri Lanka
* *) Wet season includes Maha season in Sri Lanka

Sri Lanka, the relationship between Epo and Eps was obtained as follows:-

$$\text{Eps} = 1.09\text{Epo} + 0.74 \quad \cdots\cdots \text{(IV-21)}$$

where Eps : pan-evaporation observed by using a small pan (mm/d)
Epo : pan-evaporation observed by using a 'class A' pan (mm/d)

The estimated value of ET/Eps based on Eq. (IV-21) and Table IV-4 ranged from 0.6 to 1.3 (average: 1.0) for the Maha season and from 0.8 to 1.3 (average: 1.0) for the Yala season in the dry zone area of Sri Lanka.

In the Muda area the value of ET/Eps averaged 1.20 for the wet season crop and 1.17 for the dry season crop, while the value of ET/Eps varied from 0.9 to 1.7 with an average of 1.3 in Japan.

ET ranged from 3.0 to 7.3mm/d (average: 5.8mm/d) for the Maha season and from 5.0 to 8.0mm/d (average: 6.7mm/d) for the Yala season in the dry zone area of Sri Lanka. In the Muda area, ET averaged 5.3~5.9mm/d for the wet season crop and 6.4mm/d for the dry season crop, whereas the nationwide average in Japan ranged from 3.6 to 6.0mm/d with an average of 4.9mm/d. Values of ET and ET/Eps in the three countries are summarized in Table IV-7.

Based on Table IV-7, the ET value in the dry zone area of Sri Lanka seems to be similar to that in the Muda area. The value of ET observed in Japan was about 1~2mm/d smaller than that in these tropical monsoon areas. In the tropical monsoon area, ET increases with the growth of the paddy plant, and gradually decreases after the peak at heading time. This trend contrasts markedly with the variations of ET mainly depending on the weather conditions in Japan.

ET/Eps shows higher values in Japan than in the tropical monsoon area. This is due to the sensitive response of Eps to the weather conditions as compared with ET. Namely, the difference in Eps between the tropical monsoon area and Japan is relatively larger than that in ET. The difference in the ET/Eps value between the Muda area and the dry zone area of Sri Lanka seems to be due to the difference between the observation points for Eps under the micrometeorological conditions. Eps was observed near paddy fields in the Muda area, whereas it was observed in the meteorological enclosure far from the paddy fields in the dry zone of Sri Lanka. Accordingly, when values of ET/Epo or ET/Eps are compared, it is necessary to take account of the conditions of the observation points for Eps.

4.2 Percolation (P), seepage (S) and surface runoff (RO)

Since the measurement of RO is extremely difficult due to the flat topography in the Muda area, the movement of water was observed based on the measurement of the variation of the ponding depth in the fields and the value of (P+S+RO) was observed altogether based on Eq. (IV-2). Meanwhile, in the dry zone area of Sri Lanka where topography is comparatively steep, RO was directly measured and the variation of the ponding depth was calculated by Eq. (IV-1).

Table IV-8 shows the comparison of P, S and RO between the Muda area and the dry zone area of Sri Lanka. It is notable that (P+S) shows a high value together with RO in the dry zone area. During the paddy growth stage, (P+S) can be estimated at about 2mm/d in the Muda area and at more than 20mm/d in the dry zone area of Sri Lanka. The large difference between the two areas is caused by the difference in the natural conditions and consolidation level of the paddy fields shown in Table IV-9.

In the dry zone area, based on the face that at least 80% of (P+S) returns to the drainage canal, P can be estimated at around 4mm/d, and accordingly S amounts to more than 16mm/d.

Actually, there is an important problem in the consideration of S for the planning of irrigation schemes. Formerly, it seems that S had been disregarded in the planning of irrigation schemes. For example, in the paddy area of System H under the Mahaweli Development Scheme, P was estimated at 2~4mm/d but S was disregarded [Water Management Secretariat 1985]. Of course, in the planning of a scheme, the complete disregard of S leads to a continuous water shortage in the terminal fields. In the dry zone, the water utilization system whereby several tanks are linked together in the same river basin has been generalized for the effective use of limited water resources for a long period of time. When considering the water

Table IV—8 **Comparison of P, S and RO between Muda area of Malaysia and dry zone of Sri Lanka. (mm/d)**

Items	Muda area (Malaysia) dry season	Muda area (Malaysia) wet season	Dry zone area (Sri Lanka) Yala season	Dry zone area (Sri Lanka) Maha season
Presaturation period	(46 days)	(28 days)	(24 days)	(44 days)
P				
S	6.1	2.8	30.3	31.6
RO			13.0	19.7
Total	6.1	2.8	43.3	51.3
	(139mm)	(79mm)	(1,039mm)	(2,256mm)
Paddy growth stage	(131 days)	(125 days)	(78 days)	(81 days)
P	0.9	0.9		
S	3.8	1.2	24.4	18.3
RO			6.2	15.7
Total	4.7	2.1	30.6	34.0
	(621mm)	(266mm)	(2,386mm)	(2,757mm)
Total for one season	(177 days)	(153 days)	(102 days)	(125 days)
P				
S	4.3	2.3	25.8	23.0
RO			7.8	17.1
Total	4.3	2.3	33.6	40.1
	(760mm)	(345mm)	(3,425mm)	(5,013mm)

Table IV—9 **Comparison of natural conditions and consolidation level of paddy fields between Muda area and dry zone area of Sri Lanka.**

Items	Muda area	Dry zone area
Irrigation method	plot-to-plot irrigation	plot-to-plot irrigation
Canal density	25 m/ha	50 m/ha
Drain density	30 m/ha	50 m/ha
Gradient of fields	1/5,000 - 1/10,000	1/63
Soil texture	heavy clay	fine loamy
Coefficient of permeability	$1x10^{-7}$ - $8x10^{-6}$	$7x10^{-5}$ - $4x10^{-3}$

balance in a whole river basin, since S returns to the drainage canal (river) again as surface water, it is stored in the tanks downstream to be reused in the downstream area. Accordingly, in such a large-scale irrigation scheme covering an entire river basin, in some cases although S had not been considered during the planning, the requirements can eventually be met.

However, in case of an irrigation scheme covering a part of one river basin, it is evident that the neglect of S can not meet the requirements. Even if S can be reused in the downstream area, the net amount of S must be correctly estimated; otherwise water shortage may occur in that area. The continuous water shortage recorded in the Dewa huwa Scheme [JICA 1976], which eventually led to a change in the planning and to the diversion of water from another river basin, is probably an example of the above misconception.

In the Muda Scheme, too, S is disregarded in the irrigation planning [MADA 1977]. This is one of the main reasons why the actual consumptive use of water is 10% higher in the dry season crop and 3% higher in the wet season crop than the designed consumptive use.

4.3 Presaturation requirement (PR)

Eqs. (IV-7) and (IV-10), which account for the presaturation requirement (PR) in the Muda area, include a term expressing the effectiveness of rainfall. However, Eq. (IV-19) which indicates PR in the dry zone area of Sri Lanka does not include a term related to rainfall during the period. Therefore, PR was compared between the two areas based on the assumption that there is no rain during the presaturation period.

By substituting RF=0, IR=PR and $\triangle$TEW=135.0-(1.05$\bar{R}$-18.4) for Eq. (IV-10), the following equation can be derived:-

$$PR = 587.7 \quad (\text{when } \bar{R} \leqq 17.5) \qquad \cdots\cdots (IV\text{-}22)$$
$$PR = 587.7 - 4.02\bar{R} \quad (\text{when } \bar{R} > 17.5)$$

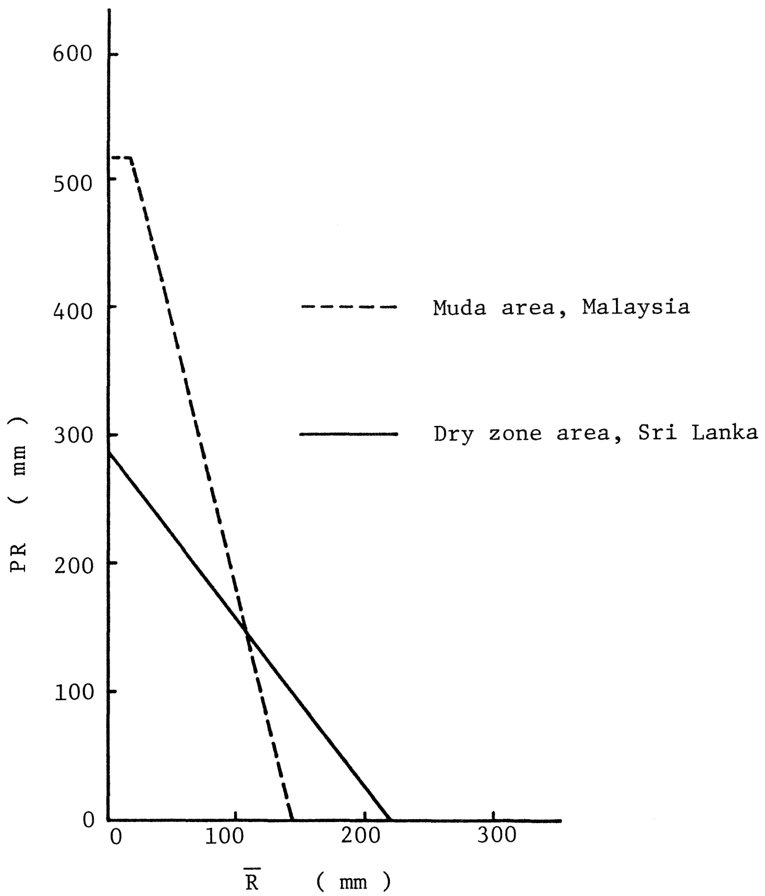


Fig.IV—14 Relationship between PR and $\bar{R}$.

where $\bar{R}$: weighted rainfall for 30 days prior to the onset of presaturation (mm)

This equation is indicated by the broken line in Fig. IV-14 together with the solid line for the dry zone area of Sri Lanka. As in Fig.IV-14, when $\bar{R}$ is less than 111mm, PR is larger in the Muda area than in the dry zone. In case $\bar{R}$ exceeds 111mm, PR is larger in the dry zone than in the Muda area. During a dry spell ($\bar{R}=0$), the Muda area needs 588mm of irrigation water for the completion of presaturation, whereas the dry zone needs only 286mm. This is caused by the differences in the canal density and topographical gradient between the two areas. It is recognized from this figure that the high presaturation requirement under dry weather is one of the major constraints to the stability of rice double cropping in the Muda area.

The relationship between $\bar{R}$ and PR indicates the speed of water flowing in the paddy fields. The more ($PR/\bar{R}$) approaches 1.0, the faster water flows on the surface of the paddy fields. The larger ($PR/\bar{R}$) becomes, the slower the flow. In the consolidated paddy fields in Japan, the value of ($PR/\bar{R}$) can be estimated at 1.0.

5. Rainfall in the irrigation area

Rainfall plays an important role in the operation of rice double cropping, because rainfall brings water directly to the paddy fields without any time lag. Thus, rainfall is more effective than irrigation water which involves a conveyance loss and time lag from the reservoir to the paddy fields. Rainfall should be used in the paddy fields prior to reservoir water. In order to determine when water should be released from the reservoir, the average amount of rainfall in an irrigation area should be calculated as soon as possible. However, it is very difficult to determine the average rainfall in a large irrigation area located in the tropical monsoon area, due to the rainfall characteristics.

In this Section, only the main points of the rainfall characteristics and effective rainfall are discussed from the irrigation point of view.

5.1 Rainfall characteristics in the tropical monsoon area

In the tropical monsoon area, the monthly rainfall varies widely. In the Muda area, even though the coefficient of variation for the annual rainfall is only 13%, the monthly rainfall varies widely especially during the dry season. The coefficient of variation is 126% in January, the month with the lowest average rainfall of 41mm, and 103% in February with an average rainfall of 61mm. The smallest coefficient of variation is 28% in October, the month with the highest average monthly rainfall of 300mm (Table IV-10). Thus, rainfall is very unreliable during the drier months of the year and more reliable in the wetter months.

The second characteristic of rainfall in the tropical monsoon area is its high intensity, i.e. it comes in short heavy showers rather than long spells of continuous rain. The average intensity per rain-day is usually higher during the wet season and lower, although still high, in the drier months (Table IV-12).

Thirdly, long dry spells occur very frequently in the tropical monsoon area during the dry season. Here, the term consecutive days without rain is defined as the number of consecutive days with less than 5.0mm rain per day. Table IV-13 shows the frequency of consecutive days without rain as well as the number of consecutive days with less than 0.1mm rain per day.

Fourthly, localized rain is one of the characteristics of the rainfall pattern in the

Table IV—10 Average monthly rainfall (mm) at Kepala Batas, Muda Scheme, Malaysia. (1947-1984)

Month	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.	Year
Rainfall	41.4	59.6	113.9	205.9	245.2	168.9	210.6	204.9	287.7	300.4	210.5	84.7	2,133.7
S.D*	52.1	61.3	59.1	107.0	94.8	76.7	95.0	80.5	110.3	84.7	85.3	66.7	287.9
C.V**	1.26	1.03	0.52	0.52	0.39	0.45	0.45	0.39	0.38	0.28	0.41	0.79	0.13

Notes : * S.D --- standard deviation
** C.V --- coefficient of variation

Table IV—11 Average number of rain-days at Kepala Batas, Muda Scheme, Malaysia. (1947-1984)

Month	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.	Year
Rain-day	4.8	5.2	9.5	15.5	17.7	15.0	17.3	16.7	19.4	21.8	18.1	9.7	170.6
S.D*	3.8	2.9	3.8	5.1	3.2	3.4	3.8	3.6	3.1	3.4	3.9	4.7	14.4
C.V**	0.80	0.56	0.40	0.33	0.18	0.23	0.22	0.21	0.16	0.15	0.22	0.49	0.08

Notes : * S.D --- standard deviation
** C.V --- coefficient of variation

Table IV—12 Average intensity of rainfall (mm per rain-day) at Kepala Batas, Muda Scheme, Malaysia. (1947-1984)

Month	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.	Year
Rainfall intensity	8.7	11.4	12.0	13.3	13.9	11.3	12.2	12.3	14.8	13.8	11.7	8.7	12.5

Table IV—13 Probability of exceedance for consecutive days without rain at Kepala Batas, Muda Scheme, Malaysia.

(days)

Probability of exceedance	Period: Dry season	Wet season	Year
10 %	(51) 80	(15) 25	(51) 80
25 %	(38) 59	(12) 21	(38) 59
50 %	(27) 42	(10) 16	(27) 42
75 %	(21) 32	(9) 15	(21) 32
90 %	(18) 30	(8) 15	(18) 30

Note : Figures in parentheses indicate the number of consecutive days with less than 0.1mm rain per day.

tropical monsoon area. In the Muda area, the changes in the correlation coefficient with the distance of rainfall between two among nine rainfall stations were analyzed as shown in Fig.IV-15. Based on the rapid decrease of the correlation coefficient with the distance shown in Fig.IV-15, it is possible to determine the rainfall characteristics in the Muda area where localized rain prevails. It is remarkable that the

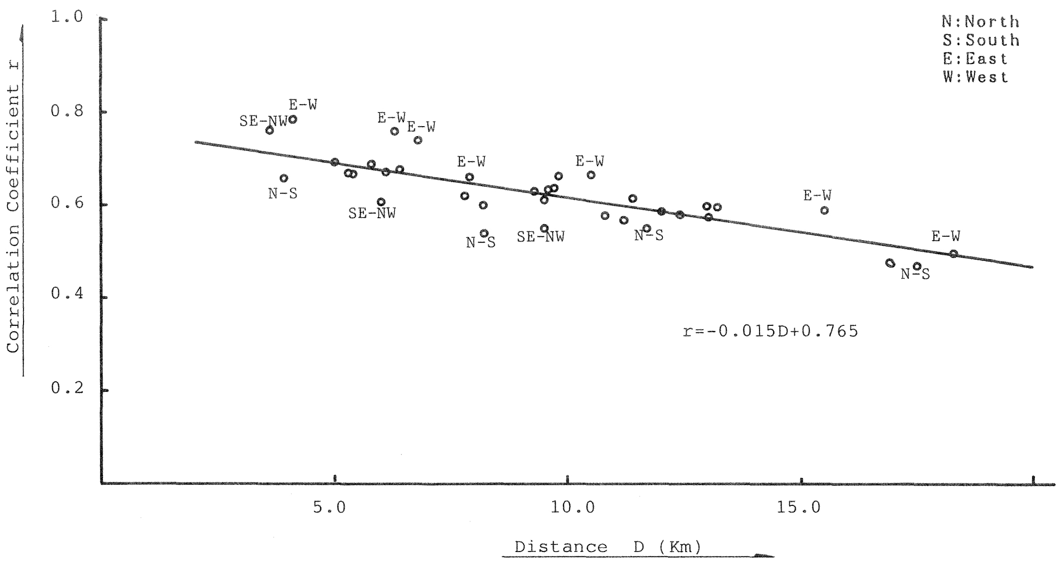


Fig.IV—15 Changes of correlation coefficient with distance for rainfall, Tunjang Drain Basin, Muda Scheme, Malaysia.

extent of the significance of the linear correlation changes depends on the locational relation (direction) as well as the distance. In particular, in the case of the locational relation of the East and West directions, the linear correlation is becoming more highly positive. On the other hand, the linear correlation is becoming more negative for the locational relation of the North and South directions. It seems that this trend is closely related to the travelling direction and expanse of clouds which send rain.

Such rainfall characteristics should be clarified and ought to be reflected for proper water management.

5.2 Effective rainfall

There is a large number of definitions for the term effective rainfall [Dastane 1974, Hayes et al. 1955, Hershfield 1964, Miller et al. 1970, Ogrosky et al. 1964, etc.]. Here, effective rainfall is defined as the portion of total rainfall which is effectively used for rice cultivation. As mentioned in paragraph 2.4, ET and deep percolation (P) are considered as unavoidable losses and included in the effectively used water as well as the increment of TEW. In this paper, effective rainfall is based on the expression of Eq. (IV-13) together with the effectiveness for irrigation. Namely, in Eq. (IV-13), Efr·RF can be regarded as effective rainfall. The coefficient of effectiveness for rainfall (Efr) fluctuates depending on the rainfall scale, topography, drain density, field conditions and farm management. In the Muda area, Efr was estimated at 0.72 during the presaturation period and at 0.688 (Efr·RF$\leqq$150) during the paddy growth stage in the dry season crop based on the monthly data observed under the present conditions. For the approximate estimation of effective rainfall in the Muda area, Efr was adopted for the paddy growth stage. Fig.IV-16 shows the monthly average of effective rainfall in the Muda area. Based on this estimation, the average annual effective rainfall is about 1,200mm per year or 56% of the annual rainfall.

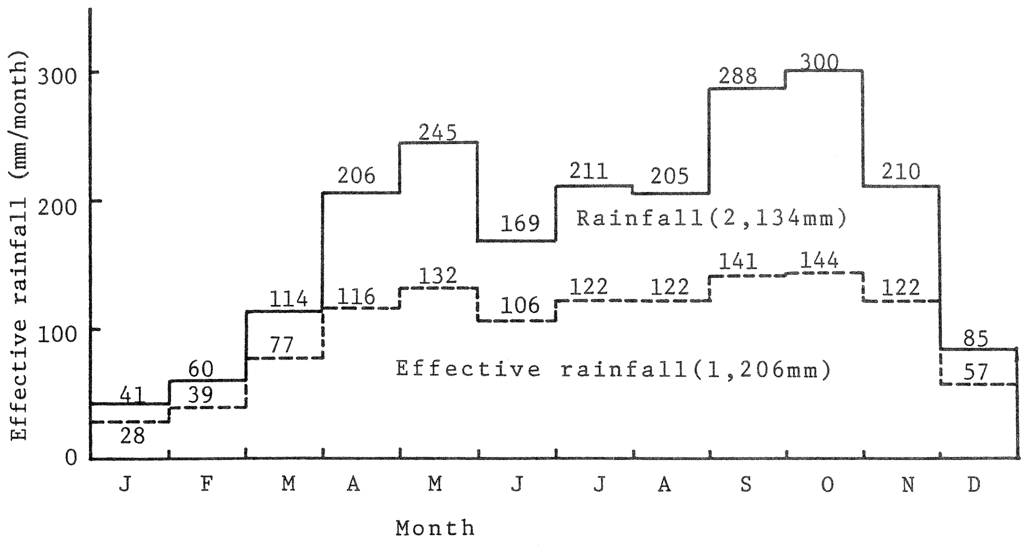


Fig. IV—16 38-year average monthly effective rainfall in the Muda area (Kepala Batas 1947 - 1984), Malaysia.

V. Water management in reservoir

In the Muda Irrigation Scheme, rice double cropping culture depends very much on the volume of water stored in the Muda and Pedu Reservoirs. This is especially true for the dry season crop, which relies almost entirely on reservoir water for irrigation. Fig. V-1 shows the changes of reservoir storage since 1970. Prior to 1975, the reservoirs were filled to capacity several times. But this has never happened again since double cropping was implemented in more than 90% of the Muda area. In fact, the reservoirs were so depleted that irrigation for the 1978 dry season crop was impossible, and again in 1983 and 1984, only half of the Muda area could be irrigated. Therefore, the shortage of reservoir water remains one of the most serious constraints on the establishment of a stable rice double cropping system. It is thus very important to evaluate the catchment yield and the actual reservoir management practiced in the past in the Muda and Pedu Reservoirs, so as to formulate better reservoir management strategy.

1. Reservoir inflow

In order to analyze the characteristics of reservoir inflow (runoff from the catchment), three approaches were adopted namely:

a) annual rainfall-runoff analysis,
b) time series analysis using statistical unit hydrograph method, and
c) the b) method but in considering seasonal changes.

The study area (1,155.1 km^2) covers the catchment of both the Muda and Pedu Reservoirs. The Muda Reservoir (area 25.9 km^2) has a larger catchment area (984.2 km^2) but a smaller storage capacity (185×10^6m^3), while the Pedu Reservoir (area 64.8 km^2) has a smaller catchment area (170.9 km^2) but a larger storage capacity ($1,047\times10^6$m^3). Water from the Muda Reservoir is channelled to the Pedu

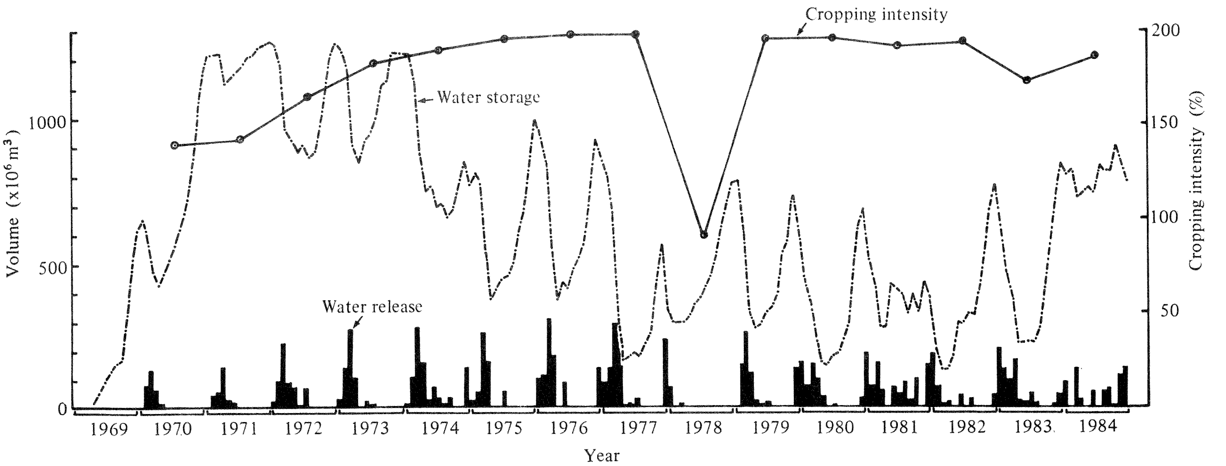


Fig. V-1 **Changes in water storage and water release from Muda and Pedu Reservoirs together with cropping intensity (1969-1984)**

Reservoir through the Saiong Tunnel (length 6.6 km), and is released through the Pedu Dam for the irrigation of the Muda Scheme.

The catchment area stretches over both the Kedah-Singgora and the Bintang Ranges (80-1,265m above sea-level), composed mostly of granite and quartzite rocks, and covered by thick primeval forest.

Water levels in both reservoirs are monitored daily at 7.00 a.m., and the storage volume is read from stage-volume curves which are computed from a topographic map. Five rainfall stations are installed around the dam sites as shown in Fig. III-1 to measure the daily rainfall.

For a strict definition of the term "runoff", the following expressions should be used:-

$$RU(t) = QIN(t) + E(t) + S(t) - \left(1.0 - \frac{RP(t)}{100}\right) \cdot R(t) \cdot AR(t) \quad \cdots\cdots\cdots (V\text{-}1)$$

$$QIN(t) = ST(t+1) - ST(t) + QT(t) \quad \cdots\cdots\cdots (V\text{-}2)$$

where $RU(t)$: Actual runoff from the catchment area on day t (m^3/d)
$QIN(t)$: net inflow to both reservoirs on day t (m^3/d)
$ST(t+1)$: total amount of water stored in both reservoirs on day t+1 (m^3)
$ST(t)$: total amount of water stored in both reservoirs on day t (m^3)
$QT(t)$: total outflow from both reservoirs on day t (m^3/d)
$E(t)$: evaporation loss from the reservoirs on day t (m^3/d)
$S(t)$: seepage loss from the reservoirs on day t (m^3/d)
$R(t)$: rainfall in the reservoirs on day t (m/d)
$AR(t)$: area of reservoirs covered with water on day t (m^2)
$RP(t)$: runoff percentage in the catchment area on day t (%)

However, since only the daily net inflow QIN(t) is actually observed [MADA 1985], while the other parameters are all unknown, "runoff" will be defined in this paper as equivalent to the net inflow as expressed in Eq. (V-2). This will impose certain limitations in the interpretation of the results of the analysis but will not hinder their practical applications, as discussed in subsequent relevant sections.

For the rainfall data, the average value of all five stations was used. It must be noted that since the locations of these stations are not evenly distributed throughout the catchment areas, they may not be able to give accurate and representative rainfall data.

1.1 Annual and seasonal rainfall-runoff analyses

Using the record of daily rainfall and net inflow data covering a period of 14 years (1971 to 1984) a series of standard analyses of the annual and seasonal rainfall-runoff relationship were carried out. The results are presented as follows:-

i) Fig. V-2 shows the relationship between annual rainfall and runoff. Rainfall loss ranges from 1,300 to 1,900mm/y, or 3.6 to 5.2mm/d, for this catchment, as compared to about 500mm/y for Japanese catchments [The Japan Society of Civil Engineers 1971] where the gradient is steeper and vegetation is thinner. Runoff percentage varies from 20 to 37 with an average of 28, and is of about the same order as that of other rivers in the world [Noma and Seno 1970].

ii) Seasonal rainfall, runoff and runoff percentage are shown in Table V-1. Out of the annual mean runoff of 638mm, dry, intermediate and wet seasons bring about a seasonal runoff of 110mm (17%), 159mm (25%) and 369mm (58%), respectively.

iii) Each seasonal runoff percentage is shown as follows:

dry season : 12～60%, average 26%,

intermediate season : 14～26%, average 19%,
wet season : 27～46%, average 37%,

During the dry season, the runoff percentage varies widely due to the low proportion of direct runoff and the variable rainfall pattern. In the intermediate season, the runoff percentage becomes minimum due to the reduced base flow associated with the low precipitation during the previous dry season, and low direct runoff percentage

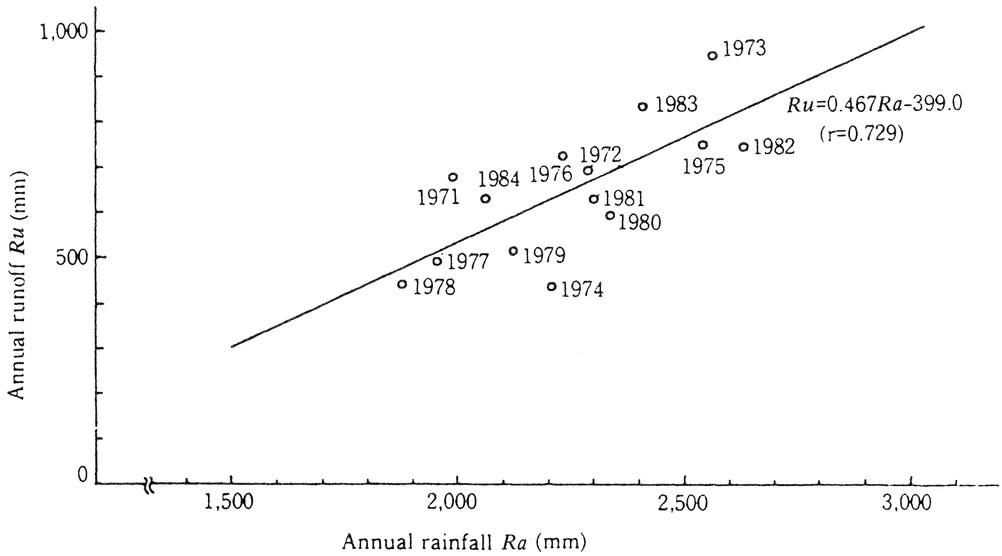


Fig. V—2 Relationship between annual rainfall and annual runoff in the catchment area of Muda and Pedu Dams (Muda Scheme, Malaysia).

Table V—1 Seasonal rainfall, runoff and runoff percentage in the catchment area of Muda and Pedu Dams (Muda Scheme, Malaysia).

Year	Dry season (Jan.-Apr.)			Intermediate season (May-Aug.)			Wet season (Sept.-Dec.)			Annual total		
	Rainfall (mm)	Runoff (mm)	R.P.[1)] (%)	Rainfall (mm)	Runoff (mm)	R.P.[1)] (%)	Rainfall (mm)	Runoff (mm)	R.P.[1)] (%)	Rainfall (mm)	Runoff (mm)	R.P.[1)] (%)
1971	360.6	216.9	60.1	656.8	139.5	21.2	986.5	322.0	32.6	2,004.0	678.4	33.9
1972	528.4	90.5	17.1	426.8	92.8	21.7	1,329.0	511.1	38.5	2,284.3	694.3	30.4
1973	483.0	258.1	53.4	1,052.1	273.4	26.0	1,026.3	414.9	40.4	2,561.4	946.4	36.9
1974	427.8	117.2	27.4	827.1	60.4	7.3	953.9	257.7	27.0	2,208.9	435.4	19.7
1975	555.3	113.2	20.4	939.6	156.9	16.7	1,048.7	480.9	45.9	2,543.6	751.0	29.5
1976	363.3	108.9	30.0	891.4	192.8	21.6	953.9	422.7	44.3	2,208.9	724.4	32.8
1977	174.3	55.7	32.0	816.5	123.7	15.2	965.1	312.8	32.4	1,955.8	492.2	25.2
1978	341.2	55.9	16.4	722.4	121.1	16.8	813.0	263.8	32.4	1,876.7	440.8	23.5
1979	410.2	49.8	12.1	833.7	161.1	19.3	881.5	305.3	34.6	2,125.4	516.2	24.3
1980	385.3	56.1	14.6	936.9	130.4	13.9	1,016.2	409.9	40.3	2,338.3	596.4	25.5
1981	429.8	89.1	20.7	953.1	245.4	25.7	916.3	301.7	32.9	2,299.2	636.2	27.7
1982	630.3	109.4	17.4	895.4	214.2	23.9	1,102.8	423.4	38.4	2,628.5	746.9	28.7
Mean	424.1	110.1	26.0	829.3	159.3	19.2	999.4	368.9	36.9	2,252.9	638.2	28.3

1) : Runoff percentage $=\frac{\text{Runoff}}{\text{Rainfall}}\times 100(\%)$.

as the infiltration capacity is still high in the catchment area. The runoff percentage becomes maximum in th wet season due to the high direct runoff. The net runoff during the wet season accounts for more than 50% of the annual runoff.

iv) It is recognized that the runoff percentage is in inverse proportion to rainfall in the dry season. However, in the intermediate and wet seasons, the relation becomes positive. Especially, the regression coefficient between rainfall and runoff percentage becomes maximum in the wet season. It is possible to consider that the gradient of the regression line reflects the sensitivity of the response of direct runoff to rainfall. The negative regression coefficient in the dry season is caused by the small proportion of direct runoff to base flow.

On the other hand, it is known that water infiltration into dry soil (at PF higher than 3.0) decreases due to increased water repellency of the dry soil [Nakaya 1982]. Studies have to be done to examine whether this phenomenon influences water runoff in the catchments during the dry season or not.

v) Fig. V-3 shows the exceedance probability plot of annual runoff (equivalent to net inflow by definition). This is compared to the estimated annual runoff (net

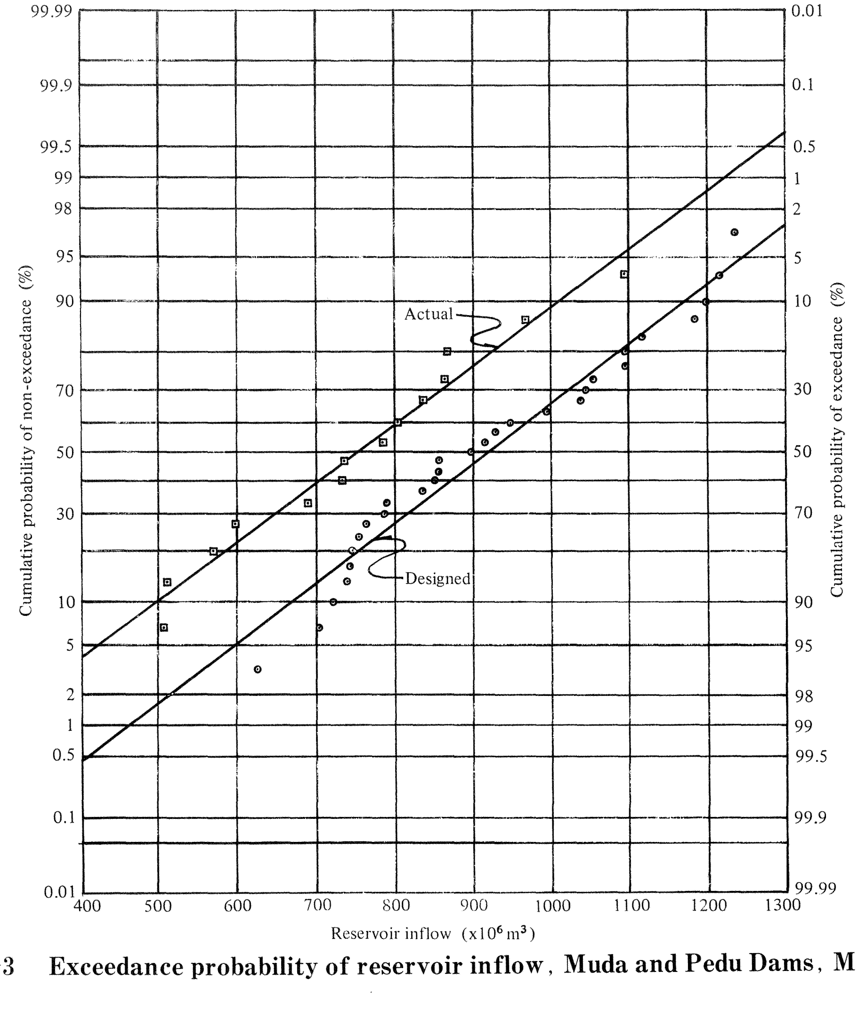


Fig. V—3 Exceedance probability of reservoir inflow, Muda and Pedu Dams, Malaysia.

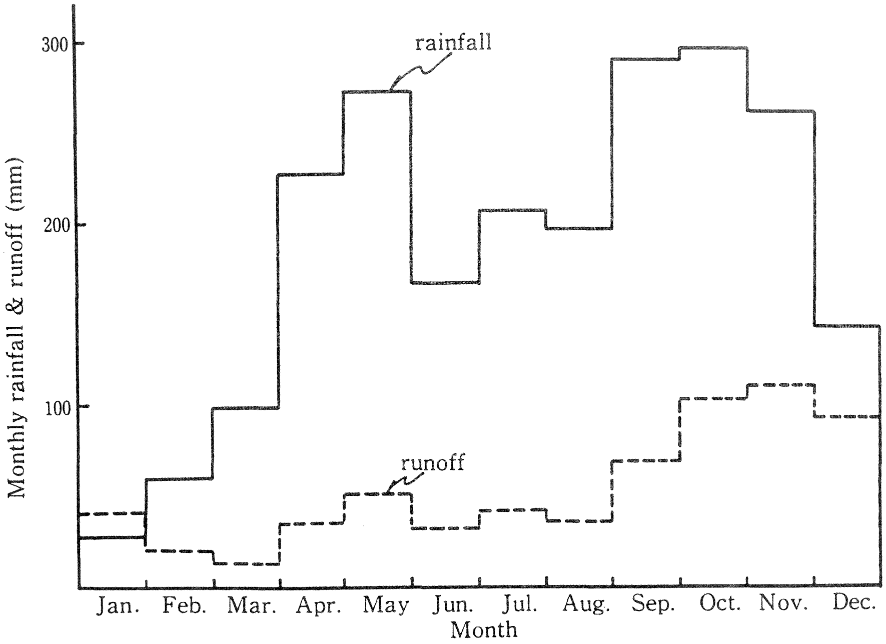


Fig. V—4 Relationship between rainfall and runoff in the catchment area of the two dams (mean of 14 years, 1971-1984), Muda Scheme, Malaysia.

inflow) outlined in the Feasibility Report for the Muda Scheme [MADA 1977]. In a "normal"year (with exceedance probability of 50%), the actual annual runoff from the catchments is only 740 million cubic meter or 640.7mm depth, as against the designed value of 925 million cubic meter or 800.9mm depth, or about 20% lower. This indicates a much more serious situation than that anticipated in the Feasibility Report for the scheme, in the possibility of failure to meet the water demand.

vi) Based on the relationship of mean monthly rainfall and runoff shown in Fig. V-4, an interesting observation is that runoff seems to lag behind rainfall over about three months.

1.2 Time series analysis of rainfall-runoff relationship

1) Method of Analysis

Several methods are commonly used for the time series analysis of rainfall-runoff. Here, the statistical unit hydrograph method was chosen. This statistical method is based on the assumption that rainfall and runoff can be considered respectively as the input and output of a black box, and their relationship is a linear system, which can be expressed by the impulse response function series called the convolution integral as follows [Ito et al. 1980] :

$$ru(t) = \int_{-\infty}^{t} h(t-\tau)r(\tau)d\tau + h_0 \qquad \cdots\cdots\cdots\cdots (V\text{-}3)$$

or

$$ru(t) = \int_{0}^{\infty} h(\tau)r(t-\tau)d\tau + h_0 \qquad \cdots\cdots\cdots\cdots (V\text{-}4)$$

where ru(t) : time series of runoff from the catchment area (mm)

$r(t)$: time series of rainfall in the catchment area (mm)
$h(\tau)$: runoff kernel, i.e. statistical unit hydrograph
τ : time-lag
h_0 : constant

Eq. (V-3) can be represented by the following linear multiple regression model.

$$ru(t) = \alpha_0 + \sum_{i=1}^{L} \alpha_i \cdot r_i(t) + \varepsilon \quad \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots (V\text{-}5)$$

where α_0 α_i : partial regression coefficients, which are all unknown parameters
$r_i(t)$: rainfall (mm)
suffix i means that the lag from time t is $(i-1)$, i. e. $r_i(t) = r(t-i+1)$
L : maximum time-lag
ε : residual

The optimum unbiased estimates of α_0 and α_i can be obtained by the least square method.

Representing optimum unbiased estimates of α_0 and α_i by partial regression coefficients a_0 and a_i respectively, Eq. (V-5) can be converted as follows:-

$$Ru(t) = a_0 + \sum_{i=1}^{L} a_i r(t-i+1) \cdots\cdots\cdots\cdots\cdots (V\text{-}6)$$

where Ru(t): statistically estimated runoff (mm)

In deriving the multiple regression model, it is necessary and very important to determine the maximum time-lag (L). As it is not practical to consider infinite (∞) maximum time-lag (L), L should be given a finite and adequate value. The following criteria may be used to determine L:

(1) Time-lag should be as long as possible for better approximation.

(2) As the actual data series is finite, it is not practical to apply unreasonably long time-lag.

(3) It is necessary that the partial regression coefficients a_0 and a_i ($i = 1 \sim L$) are positive.
However, in this paper, a_0 was allowed to be negative for the following reason. The constant a_0 generally refers to the base flow in Eq. (V-6), but due to the definition of runoff as equivalent to the net inflow to the reservoirs, a_0 represents the component of seepage and evaporation losses from the reservoirs as well as base flow. Therefore, it is quite possible that a_0 becomes negative.

(4) It is necessary to evaluate the multiple regression model by employing criteria, such as multiple correlation coefficient and analysis of variance.

(5) In order to obtain reliable partial regression coefficients in the multiple regression model, it is necessary that the predictor variables are statistically independent of each other. The autocorrelation coefficients can be employed to examine the independency of the rainfall sequence.

2) Results of analysis

Using 12 year data, a series of time series analyses were carried out. The results are presented as follows:

i) Time series analysis was carried out without considering seasonality throughout 12 years (14 years for monthly rainfall-runoff analysis) on a monthly, 10-day, 5-day and daily basis. The multiple regression equations (V-7) ~ (V-10) in Table V-2(a)

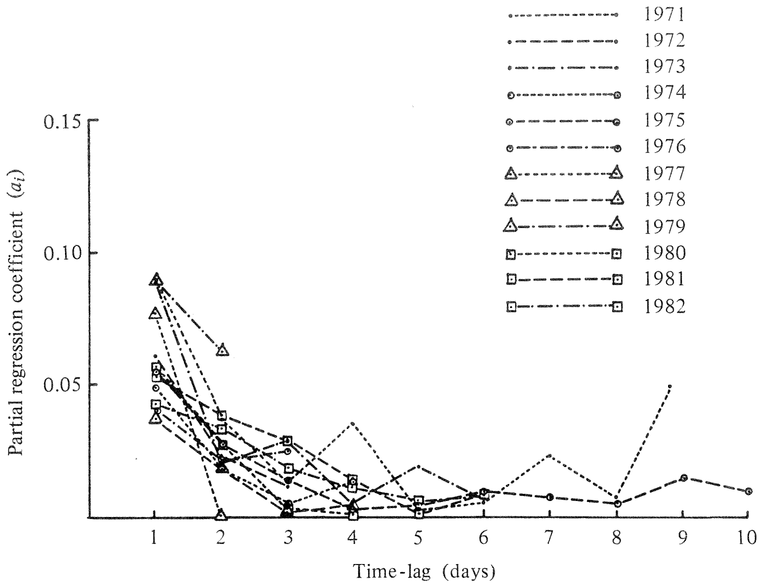


Fig. V—5(a) Statistical unit hydrograph during the dry season (Jan.-Apr.), Catchment area of Muda and Pedu Dams: 1971-1982, Muda Scheme, Malaysia.

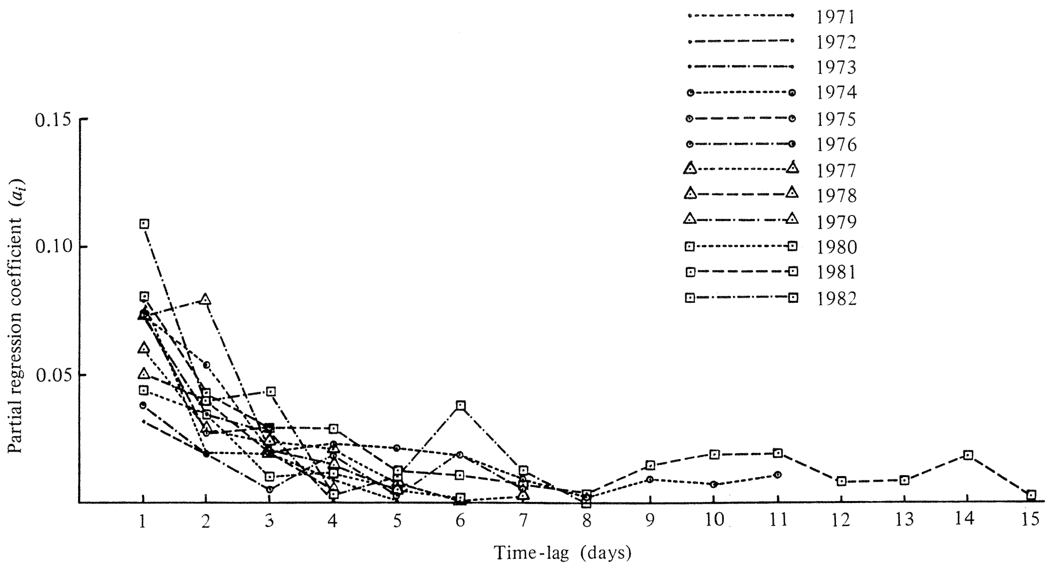


Fig. V—5(b) Statistical unit hydrograph during the intermediate season (May-Aug.), Catchment area of Muda and Pedu Dams: 1971-1982, Muda Scheme, Malaysia.

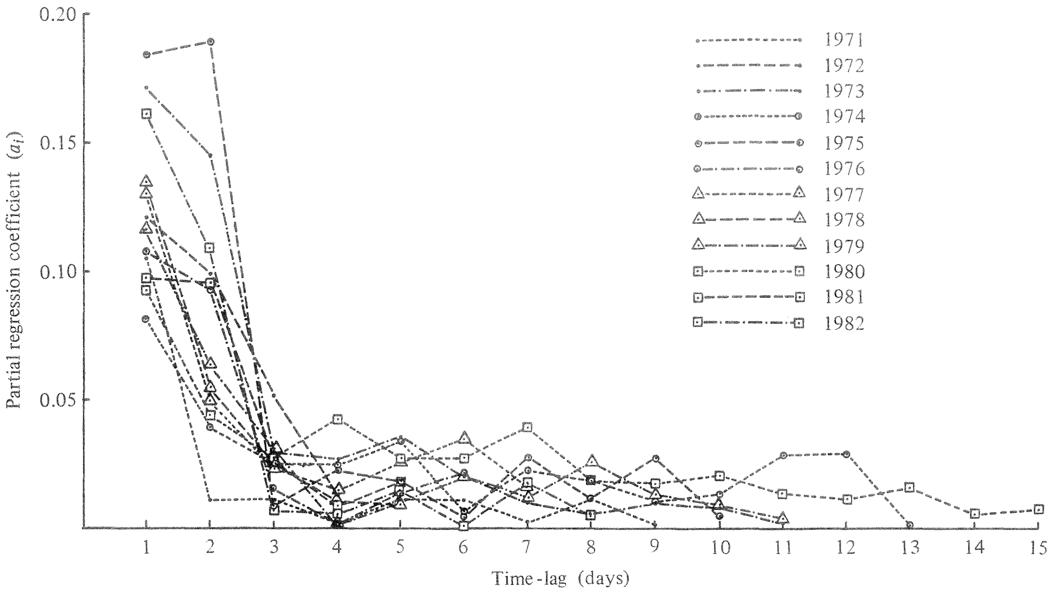


Fig. V—5(c) Statistical unit hydrograph during the wet season (Sept.-Dec.), Catchment area of Muda and Pedu Dams: 1971-1982, Muda Scheme, Malaysia.

were derived.

ii) Based on the results of the daily rainfall-runoff analysis carried out by using a multiple regression model in each season, it is possible to identify the seasonal runoff characteristics (Figs. V-5(a) ~ V-5(c)).

The total of partial regression coefficient $\sum_{i=1}^{L} a_i$ expresses the total linear runoff percentage, i.e. direct runoff percentage. Therefore, by comparing $\sum_{i=1}^{L} a_i$, the importance of direct runoff can be estimated in each season. $\sum_{i=1}^{L} a_i$ becomes increasingly larger in the order of dry season (average 0.127), intermediate season (average 0.160) and wet season (average 0.317).

iii) Modifying three sets of original equations obtained in the process of the analyses mentioned in i) and ii) so as to fit the estimated data to the observed data in each season, the three rainfall-runoff models were constructed and altogether 9 runoff estimation equations were obtained. It appears that all the models expresses adequately the seasonality of rainfall-runoff characteristics. Tables V-2(a) & (b) show the partial regression coefficients a_0, a_i ($i = 1 \sim L$) of the obtained multiple regression equations (V-11a) ~ (V-13c) for runoff. Seasonal statistical unit hydrographs for Models II and III are shown in Figs. V-6 and V-7.

The runoff estimated by Model I is shown in Figs. V-8(a) ~ V-8(d) together with the rainfall and runoff observed during the two year period from 1981.

It is very difficult to improve the accuracy of the determination of the runoff for the dry season, because the soil moisture conditions change frequently depending on the rainfall pattern and hence modify the direct runoff characteristics in the catchment area. This is one of the limitations of the linear multiple regression model in which changes in the soil moisture conditions are not taken into account.

During the wet season, the goodness of fit was considerably improved by the application of the model consisting of Eqs. (V-11a), (V-11b) and (V-11c), but the

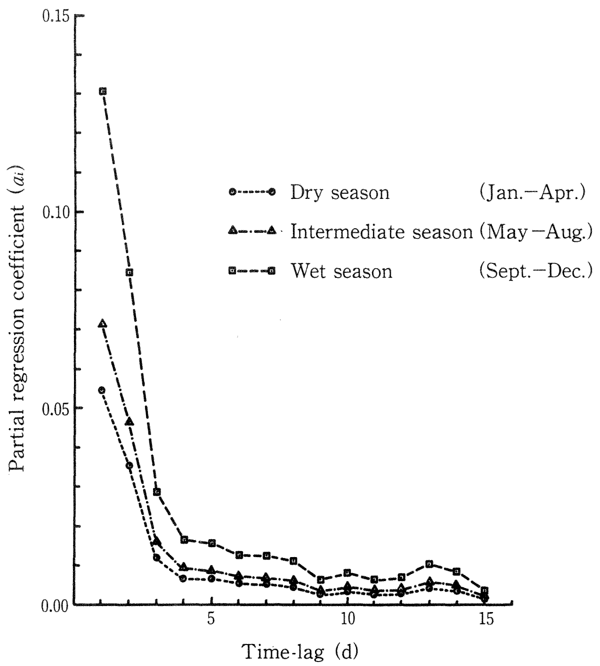


Fig. V—6 **Statistical unit hydrograph (Model II), catchment area of Muda and Pedu Reservoirs**

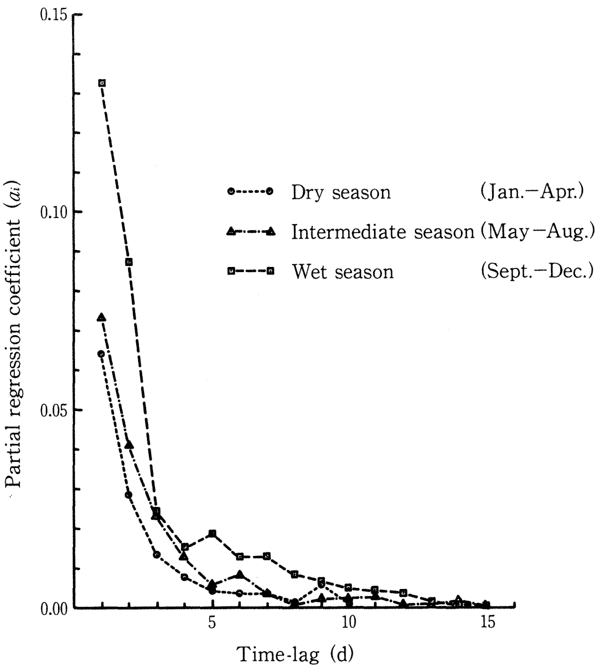


Fig. V—7 **Statistical unit hydrograph (Model III), catchment area of Muda and Pedu Reservoirs**

Table V — 2 (a) Partial regression coefficients a_0, a_i ($i = 1 \sim L$) of the obtained multiple regression models for runoff in the catchment area of Muda and Pedu Dams, Malaysia.

a_0, a_i	Monthly runoff	10-day runoff	5-day runoff	Daily runoff	—— Model I (Daily basis) Dry season	Intermediate season	Wet season ——
a_0	−111.69	−10.92	−5.21	−0.18	0.29	−0.25	−0.51
a_1	0.286	0.200	0.164	0.097	0.057	0.071	0.132
a_2	0.103	0.047	0.066	0.063	0.037	0.046	0.086
a_3	0.122	0.041	0.014	0.021	0.012	0.015	0.028
a_4	0.105	0.018	0.012	0.012	0.007	0.008	0.016
a_5	0.080	0.013	0.019	0.011	0.006	0.008	0.014
a_6	0.064	0.029	0.014	0.008	0.005	0.006	0.011
a_7	0.044	0.032	0.008	0.008	0.005	0.006	0.011
a_8	0.075	0.032	0.011	0.007	0.004	0.005	0.009
a_9	—	0.044	0.001	0.004	0.002	0.003	0.005
a_{10}	—	—	0.023	0.005	0.003	0.003	0.006
a_{11}	—	—	0.014	0.003	0.002	0.002	0.004
a_{12}	—	—	0.010	0.004	0.002	0.003	0.005
a_{13}	—	—	0.004	0.006	0.003	0.004	0.008
a_{14}	—	—	0.028	0.004	0.003	0.003	0.006
a_{15}	—	—	0.020	0.000	0.000	0.000	0.000
a_{16}	—	—	0.013	0.001	0.000	0.000	0.001
a_{17}	—	—	0.027	0.001	0.001	0.001	0.001
a_{18}	—	—	—	0.006	0.003	0.004	0.008
a_{19}	—	—	—	0.007	0.004	0.005	0.009
a_{20}	—	—	—	0.005	0.003	0.004	0.007
a_{21}	—	—	—	0.003	0.002	0.002	0.004
a_{22}	—	—	—	0.005	0.003	0.004	0.007
a_{23}	—	—	—	0.006	0.003	0.004	0.008
a_{24}	—	—	—	0.003	0.002	0.002	0.004
a_{25}	—	—	—	0.007	0.004	0.005	0.009
a_{26}	—	—	—	0.007	0.004	0.005	0.010
a_{27}	—	—	—	0.007	0.004	0.005	0.010
Eq.[1]	(V-7)	(V-8)	(V-9)	(V-10)	(V-11a)	(V-11b)	(V-11c)
MCC[2]	0.882	0.786	0.766	0.700	0.536	0.671	0.762
SE[3]				1.738	1.252	1.212	2.069
CV[4]				1.000	1.433	0.936	0.684

Notes : 1) Eq. : Equation.
2) MCC : Multiple correlation coefficient.
3) SE : Standard error of estimate.
4) CV : Coefficient of variation.

Table V-2(b) **Partial regression coefficients a_0, a_i (i= 1~L) of the obtained multiple regression models for runoff in the catchment area of Muda and Pedu Dams, Malaysia.**

a_0, a_i	Model II (Daily basis) Dry season	Model II (Daily basis) Intermediate season	Model II (Daily basis) Wet season	Model III (Daily basis) Dry season	Model III (Daily basis) Intermediate season	Model III (Daily basis) Wet season
a_0	0.37	−0.06	−0.01	0.44	0.08	0.25
a_1	0.055	0.071	0.131	0.064	0.074	0.133
a_2	0.035	0.046	0.085	0.029	0.041	0.087
a_3	0.012	0.016	0.029	0.013	0.023	0.025
a_4	0.007	0.009	0.017	0.008	0.013	0.015
a_5	0.007	0.009	0.016	0.004	0.006	0.019
a_6	0.005	0.007	0.013	0.003	0.008	0.013
a_7	0.005	0.007	0.013	0.003	0.003	0.013
a_8	0.005	0.006	0.011	0.001	0.001	0.008
a_9	0.003	0.004	0.007	0.006	0.002	0.007
a_{10}	0.003	0.004	0.008	0.001	0.002	0.005
a_{11}	0.003	0.004	0.007	—	0.003	0.004
a_{12}	0.003	0.004	0.007	—	0.001	0.004
a_{13}	0.004	0.006	0.010	—	0.001	0.002
a_{14}	0.004	0.005	0.009	—	0.002	0.000
a_{15}	0.002	0.002	0.004	—	—	0.001
Eq.[1]	(V-12a)	(V-12b)	(V-12c)	(V-13a)	(V-13b)	(V-13c)
MCC[2]	0.512	0.672	0.753	0.513	0.668	0.754
SE[3]	1.271	1.211	2.102	1.271	1.218	2.099
CV[4]	1.442	0.935	0.695	1.432	0.940	0.694

Notes : 1) Eq. : Equation.
2) MCC : Multiple correlation coefficient.
3) SE : Standard error of estimate.
4) CV : Coefficient of variation.

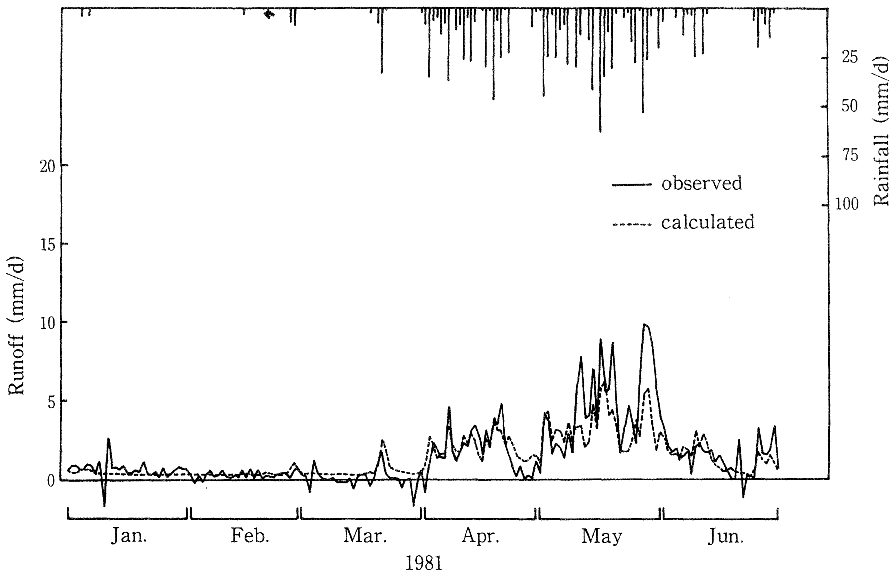


Fig. V—8(a)

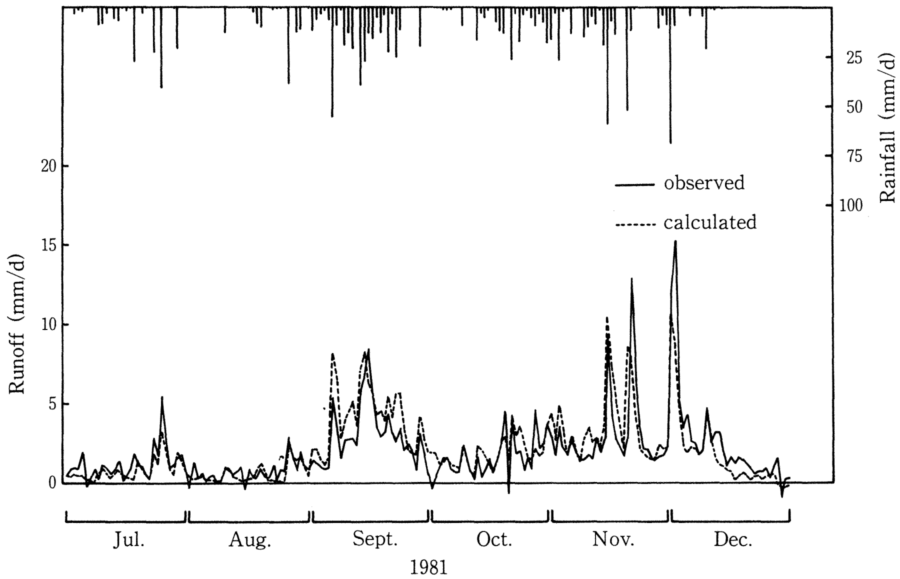


Fig. V—8(b)

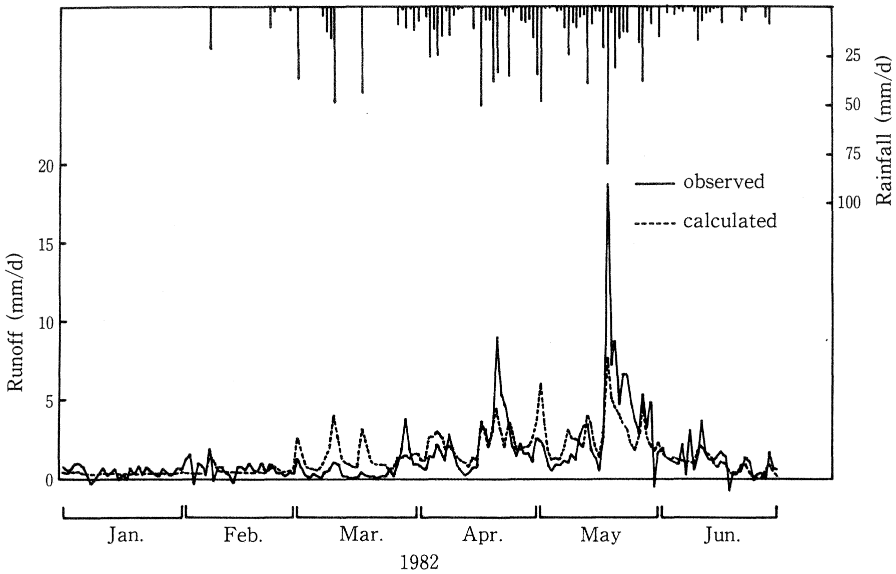


Fig. V—8(c)

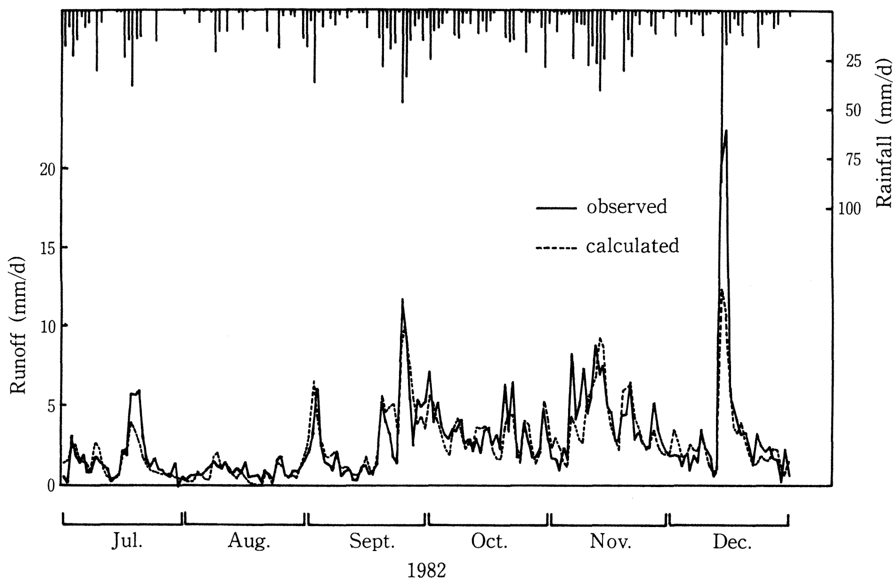


Fig. V—8(d)

Fig. V—8(a)～8(d) **Comparison between observed daily runoff and calculated daily runoff by Eqs. (V-11a), (V-11b) & (V-11c), (catchment area of Muda & Pedu Dams : 1981 - 1982), Malaysia.**

flood runoff was still underestimated.

However, for the estimation of long-term runoff for irrigation planning, these models appear to be adequate enough.

1.3 Conclusions and recommendations

The analysis carried out in this section is based on the mean value of rainfall of five stations which are installed around the dam sites only. Thus it is desirable to set up a large number of rainfall stations inside of the catchment area to improve the analysis further.

Based on the annual rainfall-runoff analysis, it became clear that the water demand in the Muda area cannot be met by the runoff from the catchment alone. Therefore, in order to cover the water deficit, it is strongly recommended to adopt every measure available such as recycling of water, effective use of uncontrolled river flow and rainfall, improved field water management, etc.

It may be considered that deforestation would increase the runoff percentage in the catchment area and improve the water supply and demand relation in the Muda Scheme. However, deforestation would result in an increased frequency of flood and would provide silting in the two reservoirs as well as the destruction of ecosystems in the catchment area. The tropical forests in the catchment area should be preserved in their totality.

It was reported that induced artificial rain (cloud seeding) had been able to alleviate drought in the past. However, as the runoff percentage is about 30% only, this method would have a limited effect on the alleviation of drought. Therefore, artificial rain should be induced in the irrigation area rather than in the catchment area.

In the time series analysis of the rainfall-runoff relationship, four multiple regression equations, of which the criterion variable is runoff and predictor variable is rainfall for the specified periods of one month, 10-day, 5-day and 1-day were derived under the assumption that the rainfall-runoff relation is linear throughout the year. These equations can be used for the setting of the water release schedule from reservoir.

However, for the daily runoff estimation, it is desirable to apply the multiple regression models obtained by taking account of the seasonality of the runoff characteristics. In choosing a model based on these four equations, both accuracy and simplicity which depend on the purpose of application should be considered.

In adopting the runoff equations (models), it is necessary to keep in mind that these were obtained from the irrigation point of view.

For further analysis, it is necessary to determine the limit for the adoption of the linear prediction by taking account of the Fixed Maximum Rainfall (F.M.R.) or the Fixed Maximum Discharge (F.M.D.). However, it seems meaningless to introduce nonlinear analysis under the current accuracy of existing rainfall and runoff data. It is strongly recommended for non-linear analysis and flood runoff analysis to incorporate the entire observation system of rainfall and runoff into a reliable system based on hourly-observation.

2. Management of water release from the reservoir

The objective of reservoir management is basically to minimize ineffective water release and optimize the use of the stored water. In this section, actual management system and resultant characteristics of storage fluctuations were analyzed using daily data on reservoirs collected for the past 15 years. Subsequently, some practical operation rules are proposed for consideration.

2.1 Operation facilities at the reservoirs

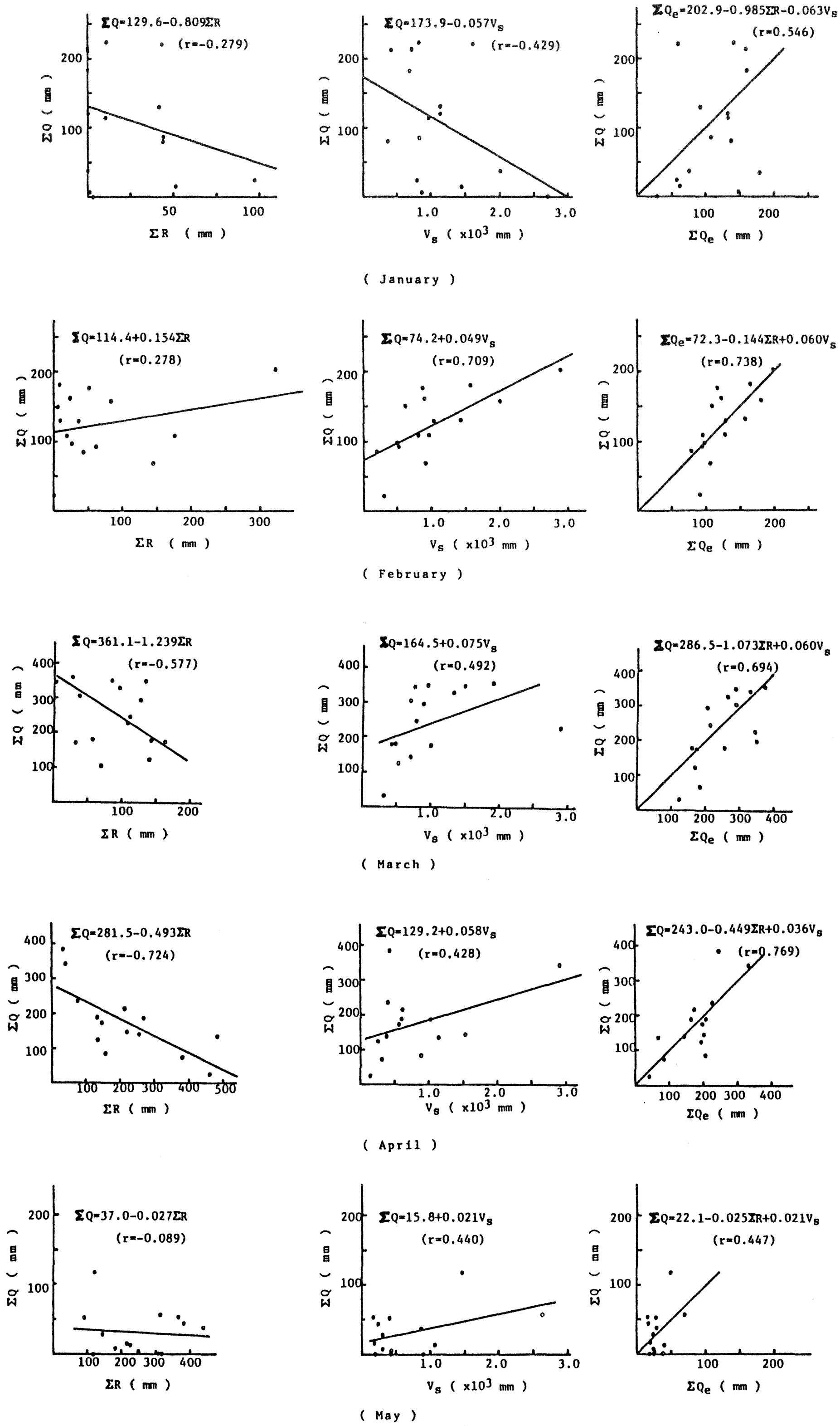
The Muda and Pedu Reservoirs are connected by a tunnel called Saiong Tunnel. It is concrete-lined, horseshoe in section, 4,483mm high, 4,419mm wide, and 6.8 km long. Control gates are provided at both ends. The gate at the Muda Reservoir side is referred to as intake gate, while the other is called outfall gate. These gates are similar in design and operation, except that the intake gate is sealed against water pressure from the direction of the Muda Reservoir only, while the outfall gate is sealed for either direction.

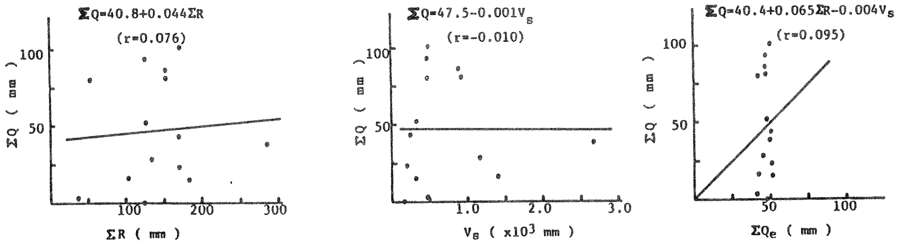
The crest level of the Muda Dam's spillway is set at +100.6m MSL, about 3.1m higher than the 97.5m spill level of the Pedu Dam. If the water level in the Pedu Reservoir reaches the maximum level, additional storage capacity of 30.8 million cubic meter can be obtained in the Muda Reservoir by closing the intake gate of the Saiong Tunnel which allows the Muda Reservoir water level to rise. Subsequently, the tunnel's gate should be manipulated to maximize storage. Storage capacity can be increased, if necessary, by raising the crest level of the Pedu Dam's spillway with sand bags.

The totality of the irrigation water for the Muda Irrigation project is released via the Pedu Dam and conveyed by the Sungai Pedu and Sungai Padang Terap (sungai means river) to the Pelubang Headworks some 67km downstream. Two 102-inch diameter welded steel pipes, encased in reinforced concrete and set in the rock below the foundation of the Pedu Dam, form the culverts which effect the release of water through the dam. Each culvert has a large concrete bell-mouth intake protected by a bar screen. Guard valves (butterfly type) are provided at the upstream ends, and these are housed in a chamber accessible through a central gallery. Hollow-jet valves are installed at the downstream ends. They are angled upward at 22.5 degree, and discharge water into a stilling basin. The valve is opened or closed by positioning a mushroom head in relation to the stainless steel throating in the valve body, using hydraulic cylinders. The valves should be opened slowly and in stages, so as to build up the water level in the stilling basin to cushion the impact of water jets, to avoid serious erosion problem, especially for high discharge. Setting for both valves should be approximately equal. The daily setting of these valves is an essential part of reservoir management. Instructions for operation are radioed from the control center of MADA in Alor Setar, and the technician on duty at the dam adjusts the valve settings based on the discharge curves calibrated for various heads and openings [DID 1966].

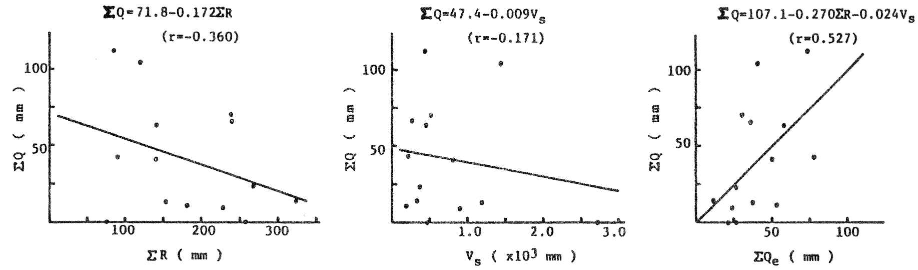
2.2 Actual management of dam release

In order to understand the present management strategy, water release date collected for the past 15 years were analyzed. Fig. V-1 shows the monthly release from the Pedu Reservoir along with the storage volume in cubic meters. Table V-3 shows the monthly release expressed in millimeter depth of water per unit irrigated area. It should be noted that 82% of the average amount of water is released (909mm) each year during the five dry month period from December to April. In particular, 26% is released in March and 19% in April, which together account for about half of the annual release. This shows that the bulk of reservoir water is used

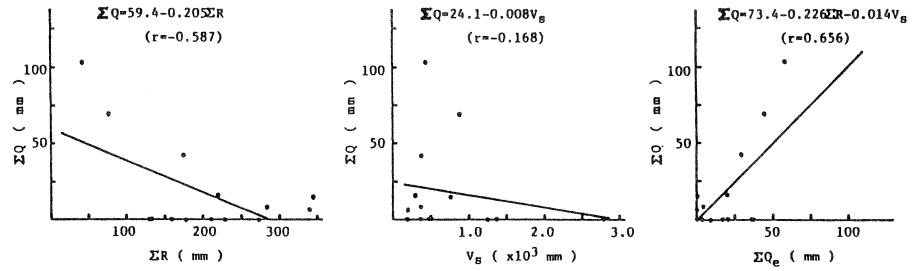

ΣQ=129.6-0.809ΣR
(r=-0.279)
ΣQ (mm)
ΣR (mm)
ΣQ=173.9-0.057Vs
(r=-0.429)
Vs (x10^3 mm)
ΣQe=202.9-0.985ΣR-0.063Vs
(r=0.546)
ΣQe (mm)
(January)
ΣQ=114.4+0.154ΣR
(r=0.278)
ΣQ=74.2+0.049Vs
(r=0.709)
ΣQe=72.3-0.144ΣR+0.060Vs
(r=0.738)
(February)
ΣQ=361.1-1.239ΣR
(r=-0.577)
ΣQ=164.5+0.075Vs
(r=0.492)
ΣQ=286.5-1.073ΣR+0.060Vs
(r=0.694)
(March)
ΣQ=281.5-0.493ΣR
(r=-0.724)
ΣQ=129.2+0.058Vs
(r=0.428)
ΣQ=243.0-0.449ΣR+0.036Vs
(r=0.769)
(April)
ΣQ=37.0-0.027ΣR
(r=-0.089)
ΣQ=15.8+0.021Vs
(r=0.440)
ΣQ=22.1-0.025ΣR+0.021Vs
(r=0.447)
(May)



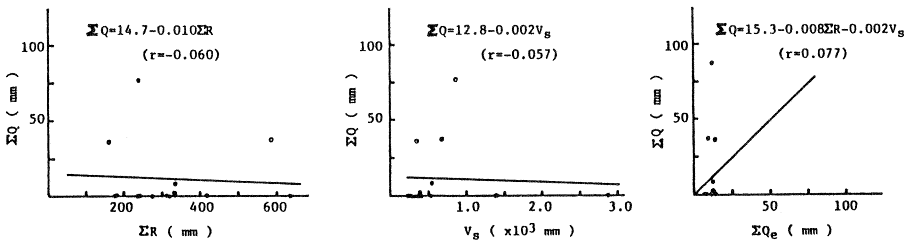
(June)



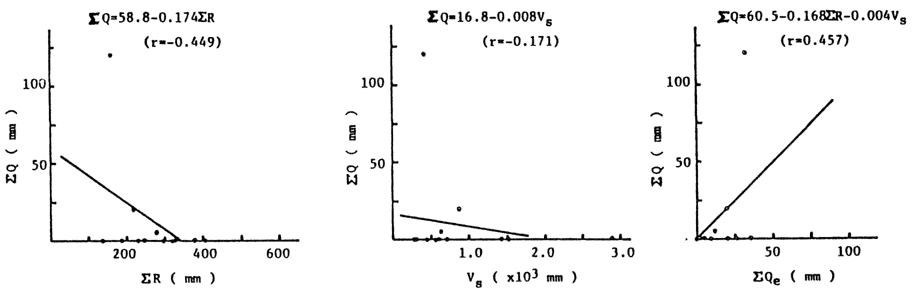
(July)



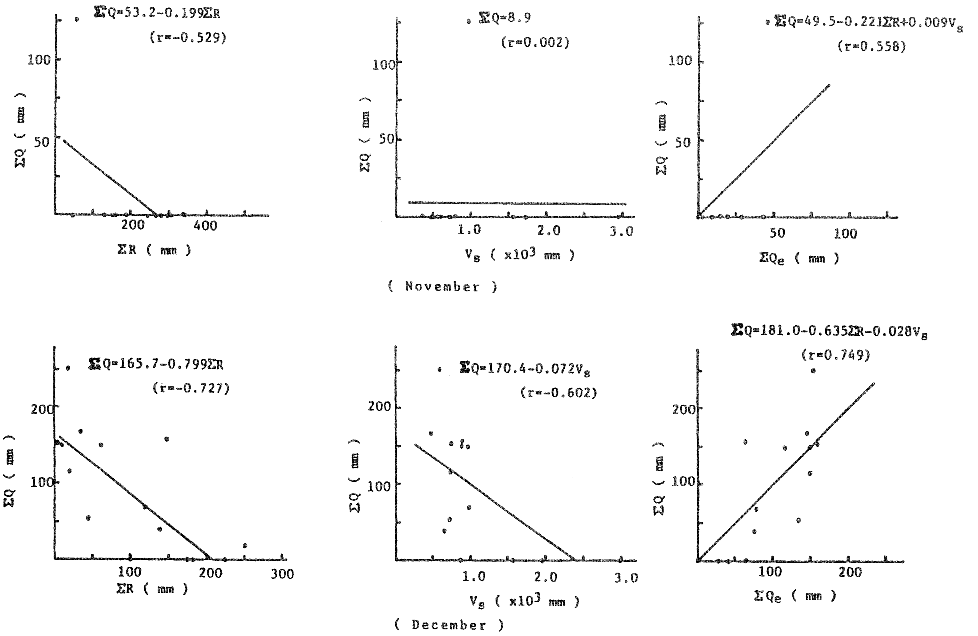
(August)



(September)



(October)



(Legend)

ΣQ : monthly water release from reservoir (mm)
ΣQ_e : calculated monthly water release from reservoir (mm)
ΣR : monthly rainfall in the irrigated area (mm)
V_s : water storage at the beginning of each month (mm)

Fig. V—9 Relationship among ΣQ, ΣR and Vs (Muda Scheme, Malaysia.)

to supply the presaturation requirement of the dry season crop.

Fig. V-9 shows, the relationship of the monthly release (ΣQ) to the monthly direct rainfall (ΣR) in the irrigated area, and to the reservoir storage (Vs) at the beginning of each month. A linear regression equation was also derived for each case. With a few exceptions, the monthly release (ΣQ) was inversely proportional to the monthly direct rainfall (ΣR), especially for the dry months.

The relationship of ΣQ and Vs for each month shows that ΣQ was directly proportional to Vs during the four months from February to May. These months correspond to the period when the demand for irrigation water is highest (to satisfy presaturation requirement and to sustain the initial growth period of the paddy plant in the dry cropping season), hence the amount of water stored in the reservoir decreases continuously and rapidly. Along with the decrease of the amount of stored water, the amount of water released is proportionally reduced. Therefore, the dwindling amount of the water stored may have prompted more careful and controlled operation, for fear of lack of water in the middle of the irrigation period.

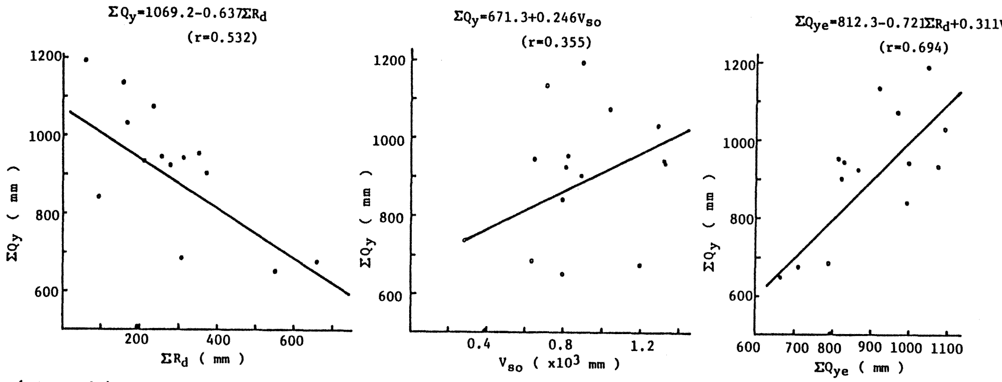
On the other hand, during the eight month period from June to January, ΣQ was either inversely proportional to Vs or showed no particular relationship at all. During this period, the dry season crop is gradually being harvested, then the wet season crop begins in August. The wet season sets in, and irrigation for the wet season crop can rely mainly on direct rainfall. At the same time, the reservoirs are being replenished. It appears that the decision to release water is unrelated to the

Table V－3 **Monthly release of water from Pedu Reservoir** (1971 - 1985 ; **except** 1978) **(mm/irrigated area)**

Month	Release of water from the reservoir				
	Mean	(%)	Max.	Min.	CV[1)]
Jan.	111.0	(12.2)	223.0	0.0	0.755
Feb.	124.7	(13.7)	202.0	22.0	0.386
Mar.	237.1	(26.1)	358.0	31.0	0.454
Apr.	175.6	(19.3)	384.0	26.0	0.557
May	30.3	(3.3)	117.0	0.0	1.084
Jun.	47.1	(5.2)	101.0	0.0	0.745
Jul.	40.6	(4.5)	112.0	0.0	0.919
Aug.	18.5	(2.0)	103.0	0.0	1.704
Sep.	11.4	(1.3)	77.0	0.0	2.006
Oct.	10.4	(1.1)	120.0	0.0	3.091
Nov.	9.0	(1.0)	126.0	0.0	3.742
Dec.	93.1	(10.3)	251.0	0.0	0.866
Total	908.8	(100.0)			

Note 1) CV : coefficient of variation

amount of water stored in the reservoir during the wet month period from June to mid-December, which corresponds to the period of replenishment of the reservoirs. However, ΣQ was clearly in inverse proportion to Vs during the months of December and January, the driest months. This is due to the release of water on the basis of the severity of water stress in the paddy fields in order to avoid crop damage, rather than on the storage conditions. As the amount of water stored in the reservoir tended to decrease during this period in the drier years, the correlation of ΣQ against Vs was



(Legend)

ΣQy : annual water release from reservoir (mm)
ΣQye : calculated annual water release from reservoir (mm)
ΣRd : rainfall during the dry months (Jan. - Mar. & Dec.) (mm)
Vso : water storage at the beginning of irrigation supply for the later stage of main-season crop (mm)

Fig. V－**10 Relationship among ΣQy, ΣRd and Vso, Muda Scheme, Malaysia**.

negative.

Fig. V-10 shows the relationship of annual water release from the reservoir (ΣQy), in terms of the total rainfall in the irrigated area during the four dry months from December to March (ΣRd), and the reservoir storage at the beginning of the year (Vso). From the graphs, it can be seen that ΣQy was inversely proportional to ΣRd and slightly proportional to Vso. The multiple regression equation obtained with a correlation coefficient of 0.694 is as follows:-

$$\Sigma Qy = 812.3 - 0.721\ \Sigma Rd + 0.311\ Vso \quad \cdots\cdots\cdots\cdots\cdots (V\text{-}14)$$

where ΣQy : amount of water released from the reservoir each year (mm)
ΣRd : rainfall during the dry months (mm) (Jan. to Mar., and Dec.)
Vso : amount of water stored in the reservoir at the beginning of each year (mm)

This regression equation appears to reflect accurately the actual pattern of water release. Although it is natural to expect that the annual release (ΣQy) will decrease in proportion to the rainfall (ΣRd), this equation shows that ΣQy actually increases when the amount of water stored (Vso) is comparatively high. For example, when Vso is 1,170mm (with a probability of exceedance Pr = 20%), ΣQy increased by about 100mm compared to the value in a normal year (Vso = 870mm, Pr = 50%), for the same rainfall conditions. In other words, more caution in controlling water release is exercised only when the amount of water stored is low, whereas when the amount of water stored is high, the control becomes lax.

As a basic method of management, attempts should be made to match the mean annual release with the mean annual inflow of the reservoir, even though the annual release fluctuates considerably depending on the field conditions in the irrigated area. In order to examine whether these criteria were met, the probability distribution of the annual release was plotted against that of the actual annual inflow as shown in Fig. V-11. The original estimated inflow for the design of the reservoirs is also shown. All the quantities had been expressed in millimeter depth of water per unit irrigated area. From this figure, it appears that the actual release was slightly lower than the designed inflow at the same probability level, and that the reservoir had been operated adequately as originally planned. However, the actual inflow, based on past data, was 20% lower than the designed value, as mentioned in Section 1. Therefore, water release in fact exceeded the reservoir inflow by as much as 14% in a normal year (Pr = 50%). This explains the acute water shortage experienced in the past years, which had caused the stoppage of irrigation supply for the entire dry season crop in 1978, and again for half of the project area in 1983 and 1984.

To determine whether the release from the reservoir had been operated without wastage, water management data collected during a six year period from 1976 to 1982 (except 1978) were analyzed. Briefly, the effective amount of direct rainfall and the contribution of uncontrolled flow (i.e. water from the rivers situated downstream of the reservoir catchment) were calculated and balanced against the natural losses in the conveyance/distribution system and the field requirement of water, from which the annual water deficiency was estimated at 795mm (Table VI-3, row (7)). This quantity represents the minimum amount of water to be supplied by the reservoir. By adding natural losses in the head race (as will be explained in Section 1 of Chapter VI), the annual gross reservoir duty was calculated to be 840mm, as shown in Table VI-3, row (8). The actual amount of water released from the reservoir is shown in row (9), with an annual mean of 904mm. Yet in spite of a

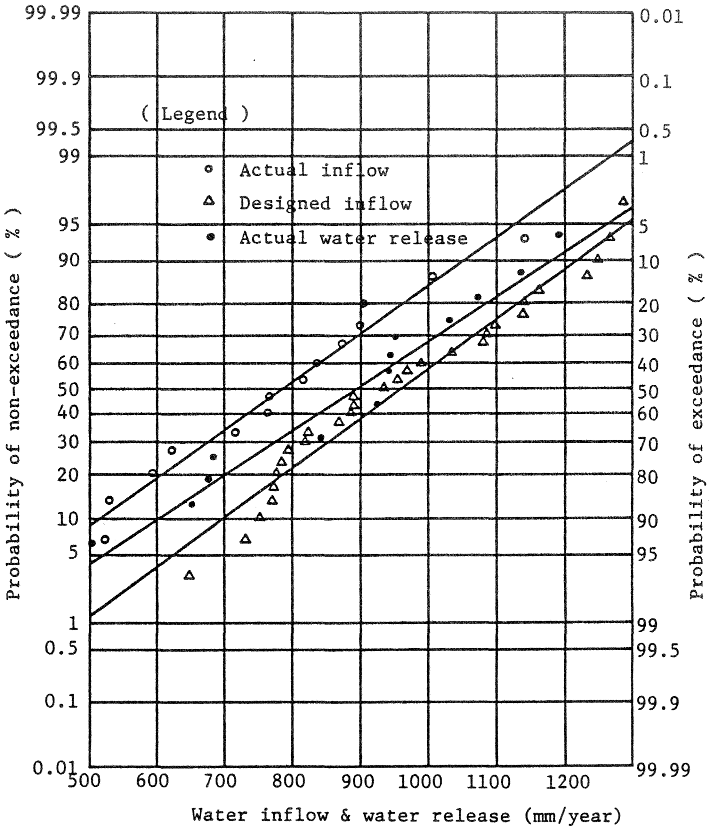


Fig. V—11 Probability distribution of reservoir inflow and water release, Muda & Pedu Reservoirs, Malaysia.

larger annual release than the gross reservoir duty, as much as 169mm of water was released wastefully, resulting in a deficiency of 105mm for a normal year. In this case, the actual operational losses of the water released from the reservoir were estimated at about 19% for a normal year.

2.3 Considerations on reservoir operation rules

In Section 2.2, it was shown that the amount of water released from the reservoir tends to decrease in proportion to the increase of the amount of rainfall in the irrigated area during the drier months, and to increase as the amount of water stored in the reservoir increases. This good management practice is achieved empirically by the officers in charge, and is not based on well defined operation rules. As Y. Senga pointed out, reservoir operation involves the need to strike a balance between two opposite objectives. The first is to promote effective release of water in response to the demand from the irrigated area, the second is to restrain release so as to conserve and restore the reservoir water in anticipation of impending or future shortages. To fulfill these two contradictory aims, it is desirable to distinguish them clearly, by establishing a "Basic Storage Curve" [Senga 1984, 1985].

Fig. V-12 shows the annual combined storage-time curve of the Pedu and Muda

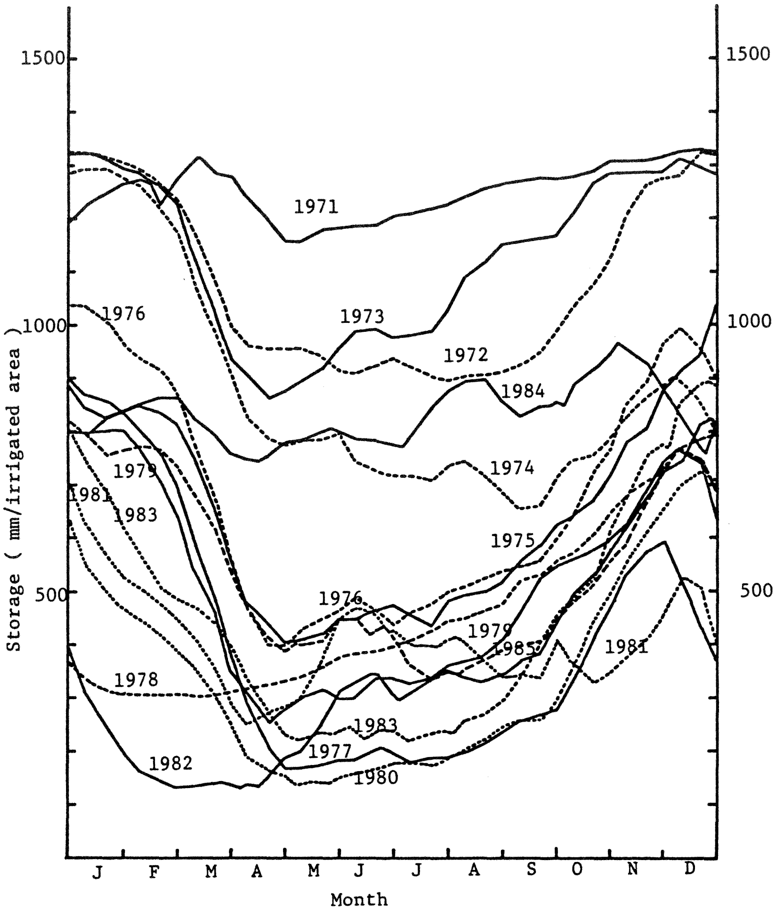


Fig. V—12 Changes in water storage in the Muda and Pedu Reservoirs, Malaysia.

Reservoirs for the past 15 years since 1971. It is evident that the amount of water stored varies from year to year, and the reservoirs cannot completely restore the annual discharge volume within the same water year. The deficit is carried over to the following year. Accordingly, once in every few years, depletion is so serious that there is no alternative but to discontinue the water supply for one season in order to build up the storage again.

Generally, reservoirs located in tropical monsoon areas store the excess runoff during the wet season for irrigation supply during the dry season. Thus the annual movement of storage can be divided into two distinct stages, i.e. the depletion and replenishment stages. It is possible to distinguish them based on the data presented in Fig. V-12. The analysis of 15 year average storage indicates that the two stages correspond to periods of 150 days from 25th December to 25th May, and 215 days from 26th May to 24th December, respectively. For subsequent discussion, the amount of depletion or replenishment refers to the net value recorded during the respective period only.

The probability of exceedance of replenishment volume is plotted in Fig. V-13.

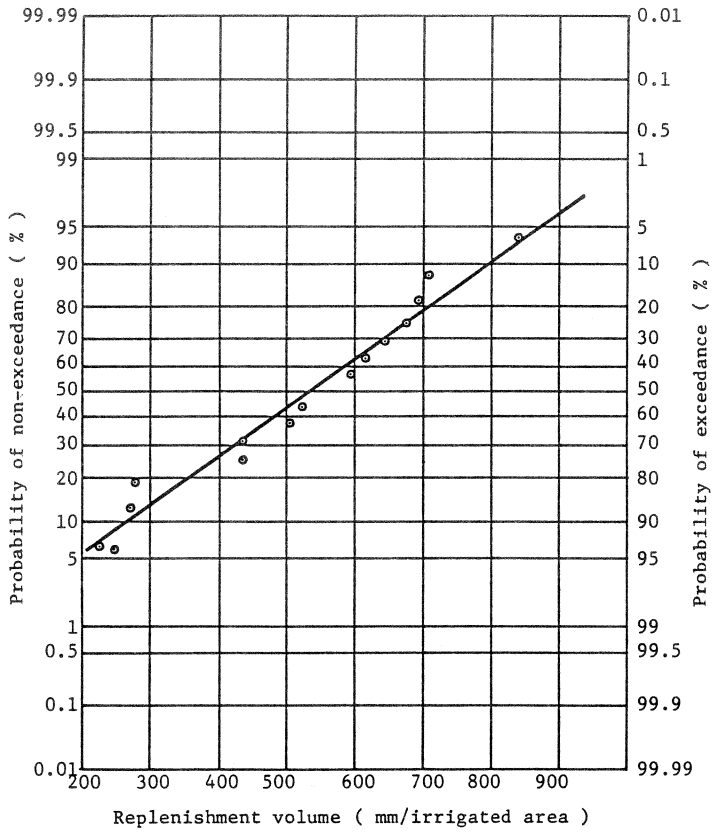
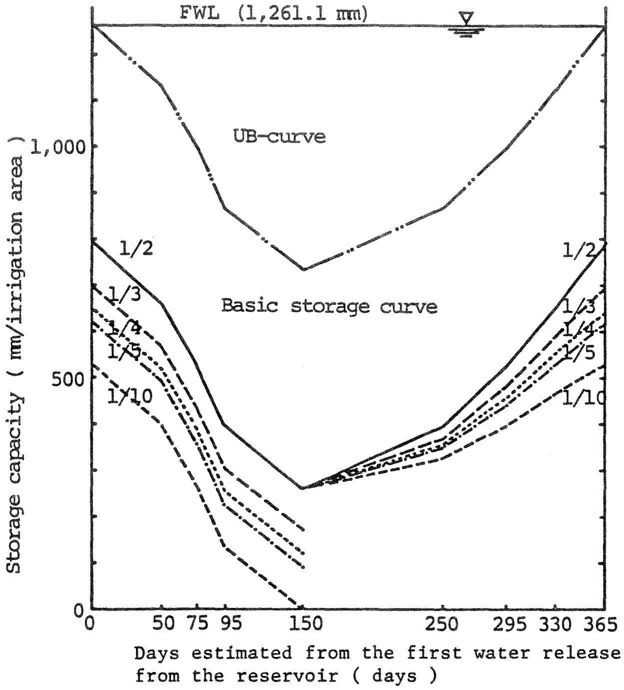


Fig. V—13 Probability distribution of replenishment volume during the replenishment stage in the two reservoirs, Muda Scheme, Malaysia.

This indicates that about 530mm can be restored in a normal year (Pr = 50%), but only 360mm for dry years with Pr = 80% (five year recurrence) and 270mm for dry years with Pr = 90% (ten year recurrence). To prevent the recurrence of acute shortage, it is desirable to regulate the water release such as to balance the amount of water depleted against that replenished for a normal year. Therefore, the decrement of storage should at least be controlled based on a water replenishment of 530mm. However, this figure may not be adequate. For drier years, it is necessary to plan for a higher value to cover the difference between the amount of water stored in a normal year. For example, a value of 170mm water for additional storage is required to cater for a dry spell occurring every 5 years, and 260mm for a dry spell occurring every 10 years.

Table V-4 shows the volume of water stored in relation to the release and subsequent replenishment of the water stored in the reservoir depending on the occurrence of a dry spell throughout the years. The corresponding number of days elapsed since water was first released for continuous supplementary supply for the wet season crop is also shown. Fig. V-14 was prepared based on Table V-4. The "basic storage curve" is that of a normal year with an exceedance probability of 50% dry spell occurring every 2 years. This graph can be applied as a standard for setting



(Legend)

UB-curve : upper boundary curve for the storage operation
1/2 : normal year (2 year recurrence)
1/3 : dry spell (3 year recurrence)
1/4 : dry spell (4 year recurrence)
1/5 : dry spell (5 year recurrence)
1/10 : dry spell (10 year recurrence)

Fig. V—14 Curve for operation rule of the Muda and Pedu Reservoirs, Malaysia.

Table V—4 Storage operation pattern for the Muda and Pedu Reservoirs

($X10^6 m^3$)
Unit : mm/96,000 ha

Change in water storage	Rate of decrease (%)					Rate of increase (%)				
	0	25	50	75	100	0	25	50	75	100
Days*)	0	50	75	95	150	150	250	295	330	365
(Return period)										
2 years	(758.4) 790	(631.2) 657.5	(504.0) 525	(376.8) 392.5	(249.6) 260	(249.6) 260	(376.8) 392.5	(504.0) 525	(631.2) 657.5	(758.4) 79.0
3	(672.0) 700	(544.8) 567.5	(417.6) 435	(290.4) 302.5	(163.2) 170	(249.6) 260	(355.2) 370	(460.8) 480	(566.4) 590	(672.0) 700
4	(624.0) 650	(496.8) 517.5	(369.6) 385	(242.4) 252.5	(115.2) 120	(249.6) 260	(343.2) 357.5	(436.8) 455	(530.4) 552.5	(624.0) 650
5	(595.2) 620	(468.0) 487.5	(340.8) 355	(213.6) 222.5	(86.4) 90	(249.6) 260	(336.0) 350	(422.4) 440	(508.8) 530	(595.2) 620
10	(508.8) 530	(381.6) 397.5	(254.4) 265	(127.2) 132.5	(0.0) 0	(249.6) 260	(314.4) 327.5	(379.2) 395	(444.0) 462.5	(508.8) 530

Notes *) Days estimated from the day on which water started to be released for the wet season crop Figures in parenthesis : million cubic meter up a schedule for reservoir operation for each water year. Generally, when the actual volume of water stored falls above the value corresponding to the volume set in the "basic storage curve", water can be released and conversely the release should be prohibited [Senga 1984, 1985]. However, this simple rule is suitable only for reservoirs which can be definitely filled up during the replenishment stage. In the case of the Pedu and Muda Reservoirs, the probability of achieving full storage from a storage volume of 260mm (or 250 million cubic meter) during the replenishment stage is only 1%. Therefore, water should not be released without any restriction even if the actual volume of water stored is above the value set in the basic storage curve. On the other hand, if the actual volume of water stored is so high that it exceeds the limit set in the UB-curve shown in Fig. V-14 in the depletion stage, then water should be released. The UB-curve represents the condition of storage which may cause spilling during the subsequent replenishment stage with a probability of more than 50%.

When the actual volume of water stored falls below the value set in the storage curve for a dry spell occurring every 4 or 5 years, one should refrain from releasing water.

For the stabilization of rice double cropping under the present conditions of the facilities, it is strongly recommended that reservoir management be based on the "basic storage curve". Any deficit should be compensated by recycling drainage water.

2.4 Conclusions

In this section, some aspects relating to the management of water release from the reservoir were discussed and summarized as follows:-

1. Based on operation records, the amount of water released during the five dry months from December to April accounted for about 82% of the annual amount released, which is 909mm. In particular, about 50% was released in March and April.
2. The actual volume of water released each year (ΣQy) was inversely proportional to direct rainfall in the irrigated area during the four dry months (ΣRd) and slightly proportional to the volume stored at the beginning of each year (Vso). The multiple regression equation obtained for the annual water release is shown as Eq. (V-14). Coefficient of correlation is 0.694.
3. With a few exceptions, the actual volume of water released each month (ΣQ) was inversely proportional to the monthly rainfall in the irrigated area (ΣR), especially during the dry months. ΣQ was directly proportional to the volume of water storage at the beginning of each month (Vs) during the four months from February to May, and inversely proportional to Vs or showed no particular relationship at all during the eight months from June to January.
4. As a general trend, the annual movement of reservoir storage can be classified into two stages, i.e. depletion stage and replenishment stage, corresponding to periods of 150 days from 25th December to 25th May, and 215 days from 26th May to 24th December respectively.
5. Based on the probability of exceedance of the annual replenishment volume during the replenishment stage, the value of 530mm (per unit cultivated area) can be estimated in a normal year. Therefore, the annual decrement of reservoir storage during the depletion stage should at least be restricted to this amount.
6. From the above findings, a "basic storage curve" was set up as shown in Fig. V

-14 and is recommended for practical reservoir storage operation.

VI. Management of conveyance and distribution system

In an irrigation system with a reservoir in the tropical monsoon area, management of the conveyance and distribution system has a significant meaning in connecting the supply and demand organically. The time lag of water flowing in the system which is an important factor determining the losses of irrigation water in the system itself ought to be kept in mind all the time for the dam operation. In this chapter, several aspects which should be considered for improving the management of the conveyance and distribution system are discussed based on the studies which were carried out in the Muda Irrigation Scheme and the dry zone area of Sri Lanka.

1. Conveyance and distribution losses

Conveyance and distribution losses can be divided into two groups, i.e. natural losses and operational losses. Natural losses include evaporation from the water surface, seepage, percolation and incidental transpiration by the vegetation growing in the water or along the banks of canals. Operational losses occur due to the lack of efficiency in the management of the conveyance and distribution system.

1.1 Natural losses

It is very important to evaluate the natural losses such as seepage, percolation and

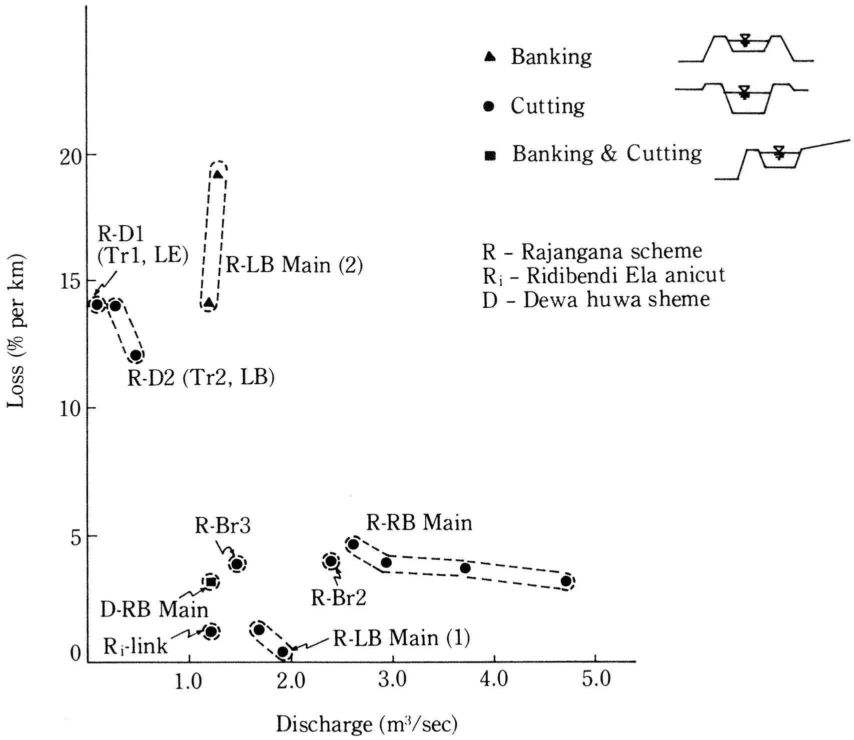


Fig. VI—1 Relationship between discharge and conveyance losses (natural losses) in irrigation channel in the dry zone area of Sri Lanka.

evaporation losses in the conveyance and distribution system for the practical operation of an existing irrigation system as well as for the planning and design of a new irrigation project, especially in the tropical monsoon area, as most of the canals are made of earth. In order to measure the natural losses from the existing canals, several methods can be adopted. The "inflow-outflow method" was found to be the most economical and convenient, and was therefore adopted in this study.

Based on the study on the natural losses in earth canals carried out in the dry zone area of Sri Lanka, some trends are summarized as follows (Table VI-1, Fig. VI-1) [Kitamura 1984] :-

In this study, the natural losses are indicated by the percentage of losses per unit length and calculated by the following formula.

$$L_n = (1-(Q_0/Q_i)^{1/\gamma}) \times 100(\%) \cdots\cdots (VI\text{-}1)$$

where L_n = natural loss rate (%/km)

Q_i = inflow into the channel section (m^3/sec)

Q_0 = outflow from the channel section (m^3/sec)

γ = length of the channel section (km)

(1) The natural losses in cut canals with a designed discharge of more than $1.0m^3/sec$ which were constructed on reddish brown earths ranged from 0.5 to 4.7%/km with an average of 2.95%/km.

Since a series of investigations on natural losses was carried out during a dry

Table VI－1 Natural losses in selected channels in dry zone

Location	Name of channel	Length of test reach (km)	Average inflow $Q(m^3/s)$	Average outflow $Q(m^3/s)$	Natural losses %/km	Natural losses %/mile	Season	Soil	Construction method of channel	Upstream point of study section
Rajangana	R.B Main ch.	3.2	4.711	4.247	3.2	5.1	'79 Yala	R.B.E[1]	cutting	1M10chs
-do-	-do-	-do-	3.717	3.296	3.7	5.8	-do-	-do-	-do-	-do-
-do-	-do-	-do-	2.952	2.602	3.9	6.1	-do-	-do-	-do-	-do-
-do-	-do-	-do-	2.617	2.242	4.7	7.4	'79/80 Maha	-do-	-do-	-do-
-do-	L.B Main ch.	2.56	1.898	1.876	0.5	0.7	'79 Yala	-do-	-do-	50m below pump unit No.8
-do-	-do-	-do-	1.674	1.620	1.3	2.0	-do-	-do-	-do-	-do-
-do-	-do-	1.04	1.312	1.051	19.2	28.9	'79/80 Maha	-do-	banking	8M3.25chs
-do-	-do-	-do-	1.213	1.036	14.1	21.5	-do-	-do-	-do-	-do-
-do-	Br. ch. No.2	1.28	2.392	2.271	4.0	6.3	-do-	-do-	cutting	2M40.1chs
-do-	Br. ch. No.3	1.44	1.455	1.374	3.9	6.2	-do-	-do-	-do-	1.8M
-do-	D-ch2, Tr2, LB	0.515	0.517	0.484	12.0	18.5	'79 Yala	-do-	-do-	0.6chs
-do-	-do-	-do-	0.281	0.260	14.0	21.4	-do-	-do-	-do-	-do-
-do-	D-ch1, Tr1, LB	0.865	99.53 l/s	87.29 l/s	14.1	21.6	-do-	-do-	-do-	48.6chs
Ridibendi Ela Anicut	Link ch. to Nikaweratiya	14.4	1.188	1.003	1.2	1.9	'79/80 Maha		cutting	0.0M
Dewa huwa	R.B. Main ch.	3.04	1.204	1.094	3.1	4.9	-do-		cutting +banking	just below gate No.2

Note : 1) R.B.E……Reddish brown earths

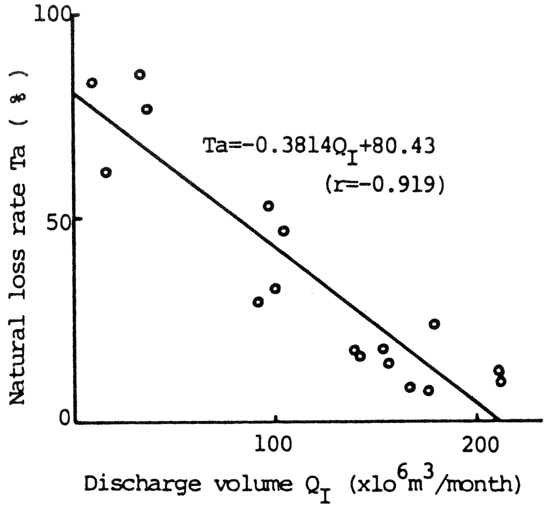


Fig.VI—2 **Relationship between discharge volume and its loss rate in the natural river (Sg. Padang Terap), Malaysia (dry months only)**

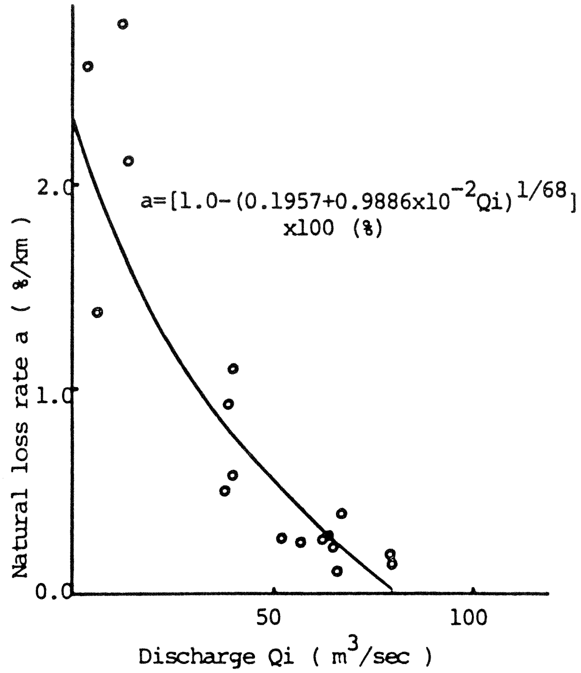


Fig.VI—3 **Relationship between discharge and natural loss rate per unit length in the natural river (Sg. Padang Terap), Malaysia (dry months only)**

spell, the figures listed above are on the safe side for irrigation planning. If the canal runs on lowland as is the case for the Link Channel to Nikaweratiya, the losses decrease and average 1.0%/km.

(2) In the case of banked canals, the loss rate is higher than in cut canals for the following two reasons:

(a) The hydraulic gradient of seepage flow, i.e. the difference between the water level of the canal and that of the groundwater table, in a banked canal is usually larger than that of cut canals.

(b) Compaction is not effective enough to control seepage and percolation in many banked canals. Therefore, it is very important for the construction and maintenance of banked canals to control compaction.

(3) In small canals where the design discharge is less than 1.0m^3/sec, the loss rate tends to be high owing to the lack of adequate operation and maintenance.

(4) The natural losses are in inverse proportion to the discharge in the same canal.

In the Muda Irrigation Scheme, the natural losses were analyzed based on the historical data of flow monitored at several points in the primary canal system.

The natural losses in the Northern Main Canal constructed on sandy, lateritic and stiff clays ranged from 0.52 to 1.88%/km with an average of 1.04%/km (Table VI-2).

In the Central Main Canal constructed on lateritic clay, the natural losses ranged from 0.0 to 0.78%/km with an average of 0.27%/km (Table VI-2).

Table VI— 2 **Natural losses in main canals in the Muda Irrigation Scheme**

Name of canal	Length of test reaches (km)	Soil	Construction method of canal	Year	Annual inflow ($x10^6 m^3$)	Annual outflow ($x10^6 m^3$)	Natural losses (%/km)	Remarks
Northern canal	16.05	sandy lateritic and stiff clays	cutting	1976	597	440	1.88	Jitra-Lana Bulu
				1977	551	438	1.42	
				1978	220	197	0.69	
				1979	499	444	0.72	
				1980	430	361	1.08	
				1981	522	446	0.98	
				1982	457	420	0.52	
				Average			1.04	
Central canal	20.86	lateritic clay	cutting	1976	546	445	0.78	Pelubang-Senara
				1977	498	455	0.34	
				1978	?	?	?	
				1979	497	475	0.17	
				1980	339	313	0.30	
				1981	553	593	0.00	
				1982	301	394	0.00	
				Average			0.27	

In the natural river (Sg. Padang Terap) between the Pedu Dam and the Pelubang Headworks which functions as a head race, the natural losses were analyzed on the basis of 7 year data, i.e. 1976 - 1982. Based on the analysis, it was found out that the river which was an effluent stream changed into an influent stream during the dry season due to the high infiltration capacity of the river basin during the season. Therefore, it is necessary to consider the natural losses even in a natural river during the dry season from January to March. Fig. VI-2 shows the relationship between the discharge volume and the loss rate in the river section extending over a distance of 68km on a monthly basis during the dry season. The relationship can be expressed by the following equation.

$$Ta = -0.3814Q_I + 80.43 \quad (r = -0.919) \quad \cdots\cdots\cdots\cdots (VI-2)$$

where Ta: total loss rate (%/68km)

Q_I: inflow into the river section, i.e. water volume released from the dam plus inflow from the river basin (x $10^6 m^3$/month)

The relationship between the discharge and natural loss rate per kilometer in the river is shown in Fig.VI-3. The natural loss rate (%/km) can be derived from Eq. (VI-2) and expressed as follows:-

$$L_n = \{1.0 - (0.1957 + 0.9886 \times 10^{-2} Q_i)^{1/68}\} \times 100 \quad \cdots\cdots\cdots (VI-3)$$

where L_n: natural loss rate in the river canal during the dry season (%/km)

Q_i: inflow into the river section including runoff from the river basin (m^3/sec)

However, during the nine months from April to December, the natural losses are negligible due to the low infiltration capacity of the river basin.

1.2 Operational losses

In addition to the natural losses, operational losses should be taken into account, especially in an irrigation area with a long conveyance and distribution system such as the Chao Phraya-Meklong Project in Thailand and the Muda Irrigation Project. The time lag of water travelling in the system is an important factor which determines the losses of irrigation water in the system itself. The flow-arrival time of water from the reservoir to the irrigation area is about 5 days in the Chao Phraya-Meklong Project [Royal Irrigation Department 1982] and 27 hours in the Muda Project [Kitamura et al. 1984]. Operational losses increase with the repeated release and interruption of the water supply from the reservoir. Operational losses for release can be calculated by the following equation (refer to Fig. VI-4 [Kitamura 1987]):-

$$L_0(\%) = \frac{Tl \times Q}{(Ti + Tl) \times Q} \times 100 = \frac{Tl}{Ti + Tl} \times 100 \quad \cdots\cdots\cdots \text{(VI-4)}$$

where L_0: Operational losses for release (%)
Q : average release discharge
Ti: necessary time (hours) for release to meet the water demand in the irrigation area
Tl: flow-arrival time of water in the conveyance and distribution system

For example, when water release from a reservoir is interrupted after three days of continuous release due to rain in the irrigation area of the Muda Scheme, the operational losses for this release, which can be calculated by Eq. (VI-4), amount

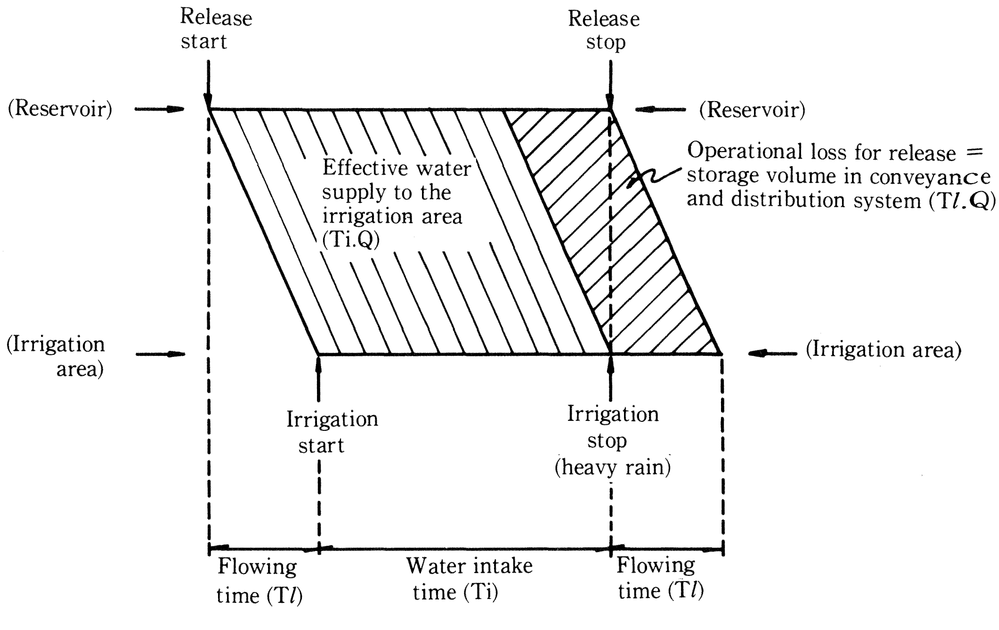


Fig. VI—4 Operational losses for release (under constant discharge)

to 27.3%. The most effective measure to reduce the operational losses in the conveyance and distribution system is to build a proper regulating reservoir in an appropriate area of the system. In the Aichi Irrigation Project of Japan, the operational losses in the main canal, whose total length is 112km, were reduced from 35% to 5% by the construction of a regulating reservoir [Yukawa 1972]. Though further studies are necessary for the determination of the storage capacity of the regulating reservoir, it seems that a regulating reservoir whose storage capacity is around 2 million cubic meter [Yoshino et al. 1986] can contribute greatly to the rationalization of water management in the canal system in the Muda Scheme.

In the dry zone area of Sri Lanka, macro-irrigation systems had been built for a long time by linking several reservoirs (tanks) together not only in the same river basin but in a larger area extending over several river basins. Especially, the tank irrigation system based on a large-scale tank linked with a large number of small-scale tanks is very popular. In such irrigation systems, a group of samll-scale tanks under a large-scale tank function as regulating reservoirs and play a very important role in water management. They have contributed significantly to the reduction of the operational losses by making water recycling possible as well as by shortening the time lag of water travelling to the terminal paddy lots. The efficiency of the tank irrigation system represented by Kala Wewa (reservoir), of which the storage capacity is 90 million cubic meter, linked with more than 60 small-scale tanks deserves admiration. However, these tank irrigation systems have seldom been operated accurately enough to fulfill their functions and it is desirable to establish suitable operation methods to achieve such objectives.

[Operational losses of side flow]

In the irrigation projects of which side flow into the conveyance and distribution system is considered as a source of water supply, such as the Muda Irrigation Project and the Chao Phraya-Meklong Project, the losses of side flow also should be added to the operational losses.

Here, operational losses of side flow were roughly estimated based on the historical data in the Muda Scheme. Generally, in order to improve the efficiency of water management in an irrigation system, the following procedures are adopted. Firstly, the deficiency of rainfall in an irrigation area should be compensated by the uncontrolled river flow as much as possible. Then, if the water supply by uncontrolled river flow is insufficient, reservoir water should be released in order to compensate for the deficit. In the following estimation, the minimum values of monthly consumptive water use observed in the SCRBD5b irrigation block for three consecutive years were adopted as monthly water requirement. Based on these values and mean monthly rainfall amount observed at Kepala Batas (Alor Setar Airport) for six years from 1976 to 1982 (excluding 1978), the deficiency of rainfall for rice double cropping was estimated as indicated in row (3) in Table VI-3 and the annual deficiency of rainfall was found to be 874 mm.

The amount of the 6-year mean monthly uncontrolled river flow reported in Chapter V is shown in row (4), and the portion of the uncontrolled river flow to be used effectively is indicated in row (5). Out of the mean annual uncontrolled river flow i.e. 763 mm, approximately 30% of the value or 235 mm is to be used effectively. On the other hand, the mean value of the uncontrolled river flow effectively used which was obtained from the actual results for 6 years (1976~1982; excluding 1978) was 155 mm in a year as shown in row (6). This is equivalent to 66% of the amount of uncontrolled river flow to be used effectively, i.e. 20% of the total uncontrolled

Table VI－3 Estimation of operational losses of uncontrolled river flow and water release from dam

(mm/irrigation area)

Items	Month	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.	Total
(1) Water consumption		158	132	352	267	254	264	217	251	198	183	186	202	2664
(2) Rainfall		2	40	80	254	255	138	210	195	263	259	198	50	1943
(3) Deficit ①	(1)−(2)	156	92	272	13	0	126	7	56	0	0	0	152	874
(4) Side flow		22	13	12	51	80	48	48	46	90	133	146	74	763
(5) S.F.T.U.E[1]		22	13	12	13	0	48	7	46	0	0	0	74	235
(6) E.U.S.F[2]		3	1	4	17	21	23	13	9	0	19	26	19	155
(7) Deficit ②	(3)−(6)	153	91	268	0	0	103	0	47	0	0	0	133	795
(8) Necessary gross dam release		166	123	268	0	0	103	0	47	0	0	0	133	840
(9) Actual dam release		141	123	229	136	17	45	25	25	7	20	0	136	904
(10) Deficit ③	(8)−(9)	25	0	(0)		0	58	0	22	0	0	0	0	105
(11) Operational loss (dam)	(9)−(8)	0	0	(97)		17	0	25	0	7	20	0	3	169

Notes 1) S.F.T.U.E : Amount of uncontrolled river flow to be used effectively (≦ uncontrolled river flow)
2) E.U.S.F : Effectively used uncontrolled river flow

river flow. Namely, operational losses of the uncontrolled river flow can be estimated at 34% of the amount of the uncontrolled river flow to be used effectively. If the operational losses of the uncontrolled river flow for January and February (31 mm) computed as natural losses are accounted for the amount of effectively used uncontrolled river flow, the coefficient of effectiveness for uncontrolled river flow amounts to 80%.

It seems that such comparatively low operational losses of the uncontrolled river flow are caused by an operational rule that the whole amount of flow is generally diverted at the Pelubang Headworks during the dry season. For the further improvement of the coefficient of effectiveness for uncontrolled river flow, the runoff estimation system for that should be set up.

Based on Table VI-3, the actual operational losses of water release from the dam throughout a year were estimated at 19% (The details were given in Chapter V).

The above estimation was actually very bold, because it was performed on the basis of the water requirement estimated from the field study carried out for three years (1984～1986) and the mean rainfall, uncontrolled river flow and water release from the dam observed for 6 years (1976～1982; excluding 1978). However, the estimation appeared to reflect the general tendency of the actual management of the conveyance and distribution system in the Muda Irrigation Scheme.

Operational losses of the uncontrolled river flow and reservoir release occur due to the lack of a monitoring system of the water conditions, rainfall forecasting system in the irrigation area and runoff forecasting system for the uncontrolled river flow. Daily monitoring and forecasting may be too difficult to perform for the irrigation systems located in the tropical monsoon area. However, by adopting the monthly, 10-day and 5-day (or weekly) monitoring and forecasting system, it seems that a considerable amount of operational losses can be reduced.

1.3 Conclusions

In this section, conveyance and distribution losses which consist of natural losses and operational losses were investigated basd on on-site and some trials. The results are summarized as follows:-

① The natural losses in earth canals vary widely due to topography and soil.

In the dry zone area of Sri Lanka, the natural losses in cut canals with a designed discharge of more than 1.0m³/sec which were constructed on reddish brown earths ranged from 0.5 to 4.7%/km with an average of 2.95%/km. In the case of banked canals, the loss rate is higher than in cut canals for two reasons.

In the Muda Irrigation Scheme, the natural losses ranged from 0.52 to 1.88%/km with an average of 1.04%/km in the Northern Main Canal and from 0.0 to 0.78%/km with an average of 0.27%/km in the Central Main Canal, respectively.

② In the natural river which functions as a head race for the Muda Irrigation Scheme, it was found out that the river which was an effluent stream changed into an influent stream during the dry season due to the high infiltration capacity of the river basin during the season. The natural losses in the natural river during the dry season from January to March can be expressed as Eq. (VI-3).

③ The operational losses are mainly decided by the time lag of water travelling in the systems. In the Muda Irrigation Scheme, the coefficient of effectiveness for uncontrolled river flow was estimated at around 80%. The actual operational losses of water release from the dam were estimated at 19%. The most effective measure to reduce the operational losses in the long conveyance and distribution system is to build a proper regulating reservoir in an appropriate area of the systems.

2. Flow-arrival time in the Muda Scheme

Irrigation system for rice double cropping culture in the tropical monsoon area of Southeast Asia, such as Thailand and the northwestern part of Malaysia is characterized by a large scale. As the tropical monsoon climate has a distinct dry season, the irrigation system is composed of a huge reservoir as water source for the dry season, long main and branch canals, and large-scale terminal irrigation blocks in which plot-to-plot irrigation prevails. Most of the large-scale irrigation schemes in the tropical monsoon area were designed and constructed on a short term basis by foreign consultants and contractors under loans from the World Bank or Asian Development Bank. Though the operation and maintenance of the irrigation systems are mainly carried out by each irrigation departments as a part of their administration, the effectiveness of water use is not easily achieved presumably because the design of the irrigation system emphasized the conveyance capacity for maximum discharge instead of time series analyses of the water movement in the system. Namely, the flow-arrival time is seldom considered in the design. To achieve an effective and rational management of irrigation facilities, it is very important to determine the time required for water to travel from the dam or headworks to the irrigation area.

In this Section a time series analysis of the flow-arrival conditions from the Pedu Dam to the irrigation area is discussed.

2.1 Flow-arrival time in the Sungai*) Padang Terap

Water released from the Pedu Dam is channeled to the Pelubang Headworks located at the upstream end of the Muda Irrigation Scheme through the Pedu and Padang Terap rivers. The distance along the natural river functioning as a head race from the Pedu Dam to the Pelubang Headworks is about 67 km and there are very few facilities for water use in this section. In order to achieve a timely release of water from the Pedu Dam to satisfy the water requirements in the irrigation area, it is essential to analyze the flow-arrival characteristics in the Pedu and Padang Terap rivers under various water release patterns. MADA endeavoured to develop a suitable and empirical method for water release.

As shown in Fig.III-1, the Pedu river represents the upper reaches extending over a distance of 34 km from the Pedu Dam to Kuala Nerang, and the lower reaches from Kuala Nerang to Pelubang Headworks are called Sungai*) Padang Terap. The upper reaches down to Kuala Nerang meander and are joined by several tributary rivers. Water level records were taken at Kapala Batas (12 km downstream from the Pedu Dam), Kuala Nerang (34 km downstream from the Pedu Dam) and the Pelubang Headworks. Hereinafter the entire river from the Pedu Dam to Pelubang is simply referred to as Sg.*) Padang Terap.

For the investigation of the flow-arrival time, unsteady flow analysis based on a mathematical model was adopted.

2.1.1 Description of mathematical model for unsteady flow analysis

(1) Basic Equations

The basic equations for unsteady flow in an open channel, i.e. the equation of motion and equation of continuity, are expressed as follows:-

$$\frac{1}{g}\cdot\frac{\partial V}{\partial t}+\frac{1}{g}\cdot\frac{\partial}{\partial x}\left(\frac{v^2}{2}\right)+i+\frac{\partial H}{\partial x}+\frac{n^2 v|v|}{R^{4/3}}=0 \cdots\cdots\cdots (VI-5)$$

$$\frac{\partial A}{\partial t}+\frac{\partial Q}{\partial x}-q=0 \qquad \cdots\cdots\cdots (VI-6)$$

where, v : flow velocity,
i : channel bed slope,
H : water depth,
x : distance,
n : coefficient of roughness,
R : hydraulic radius,
A : cross-sectional area of flow,
Q : flow discharge,
g : gravitational acceleration,
t : time,
and q : lateral inflow discharge per unit length.

These equations can be expanded to finite difference equations based on the Nakamura-Shiraishi method [1971] using the central difference method. Flow parameters including velocity, water depth, discharge, etc. can be simulated by numerical integration with respect to x (distance) and t (time). In this study, the modification using the 'Up wind difference method [Roache 1978] ' was partially adopted for the following reason:-

*) Sungai = Sg. = River

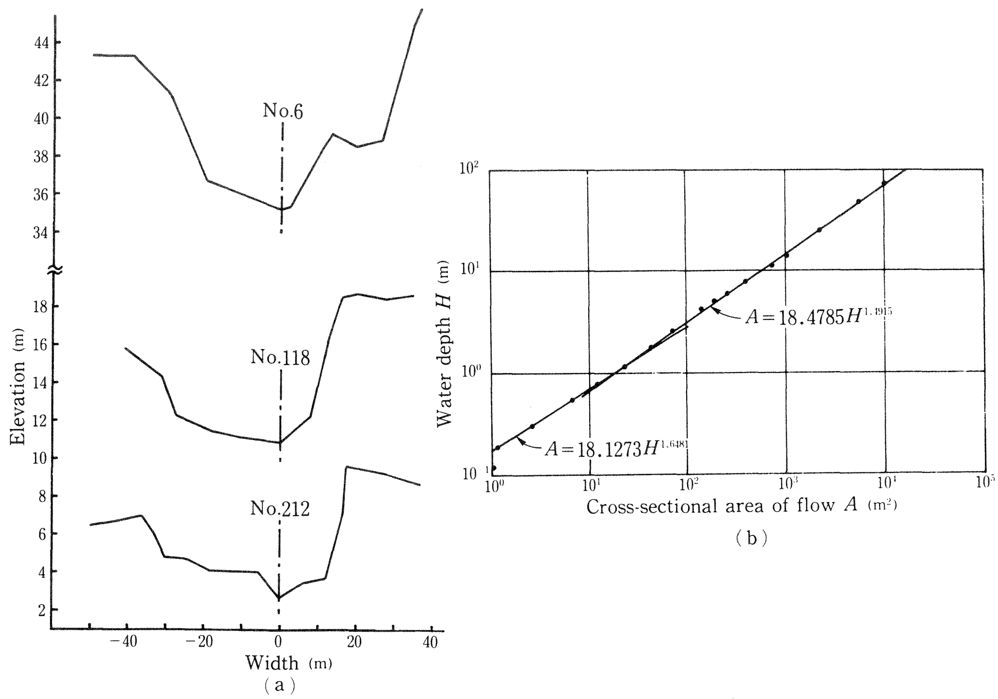


Fig. VI—5 (a)**Cross-sectional profiles at three points**; (b)**Relationship between the cross-sectional area of flow** (A) **and the water depth** (H) **at a river section (No. 118) in the middle reaches**

In the backwater-affected section near the Pelubang Headworks and extending over 18 km upstream the river, the velocity of flow (v) becomes very small due to the presence of a water depth of 6-7m and a large cross-sectional area. Therefore, the fifth term of Eq. (VI-5), i.e. $n^2v^2/R^{4/3}$ (head loss by friction), becomes very small, while the second term $\partial/\partial x\ (v^2/2g)$ becomes comparatively more significant in the motion equation. Accordingly, in the process of simulation based on the central difference method, numerical instability, indicating that the solution for the discharge is numerically unstable, occurs easily. By adopting the 'Up wind difference method', which is a method used for the analysis of air flow as well as water flow in a drainage canal [Nakamura et al. 1984], for the second term of Eq. (VI-5), such numerical instability was successfully removed.

(2) Mathematical model of the Sg. Padang Terap

a) Expression of cross-sectional data

As Sg. Padang Terap has an irregular cross-sectional profile and widens gradually as it flows to the lower reaches as shown in Fig. VI-5 (a), the following treatment of the survey data was adopted. Generally, the cross-sectional area of flow (A) can be expressed as a function of the water depth (H). The relationship between the cross-sectional area and water depth plotted on a logarithmic graph paper can be represented by 2 to 3 straight lines and expressed as follows:-

$$A_i = \alpha_i H^{\beta_i} \qquad \cdots\cdots\cdots (VI-7)$$

where α_i, β_i : coefficients

In this paper, the relationship between the cross-sectional area and water depth was obtained for every 2,000 feet (about 610m) in the river section between the Pedu Dam and Pelubang Headworks. For each cross-section, the flow area A for incremental depth H was computed and the relationship plotted on a logarithmic graph by a computer program. The curve obtained was approximated by two straight lines and the corresponding coefficients $\alpha_1, \beta_1, \alpha_2, \beta_2, \cdots\cdots$ were evaluated as described in Eq.(VI-7). Fig.VI-5(b) shows the relationship between the cross-sectional area of flow (A) and the water depth (H) at a river section in the middle reaches.

b) Outline of analytical model

The entire river from the Pedu Dam to the Pelubang Headworks was divided into sections every Δx = 2000feet, which were numbered sequentially (even number) from the upstream zone. The cross-sectional data obtained in paragraph a) are allocated to each section.

Due to the insufficient number of cross-sectional data in the tributaries, only two tributaries whose basin is comparatively large, i.e. Sg. Tekai and Upper Sg. Padang Terap, were included in the model, as shown in Fig.VI-6.

Normally, when the reservoir water is released from the Pedu Dam for the presaturation supply, little water remains in the tributaries. Water may flow backward into or out of the tributaries depending on the rise and fall of the water level in the main river. Therefore, in these simulation analyses, the following assumptions were adopted:-

It was assumed that there is always a small amount of stationary water in the river at a depth of 2-3cm (H_{min}), and that the river never becomes completely empty. When the water depth (H_i) in an adjacent mesh (upstream mesh for increasing process, downstream mesh for decreasing process) is deeper than H_{min}, Eqs.(VI-5) and (VI-6) are analyzed. However, in case H_i is smaller than H_{min}, the water depth (H_i) and velocity (v_i) for the mesh concerned are set to H_{min} and 0(zero) respectively [Iwasaki 1975], and then the analysis is continued.

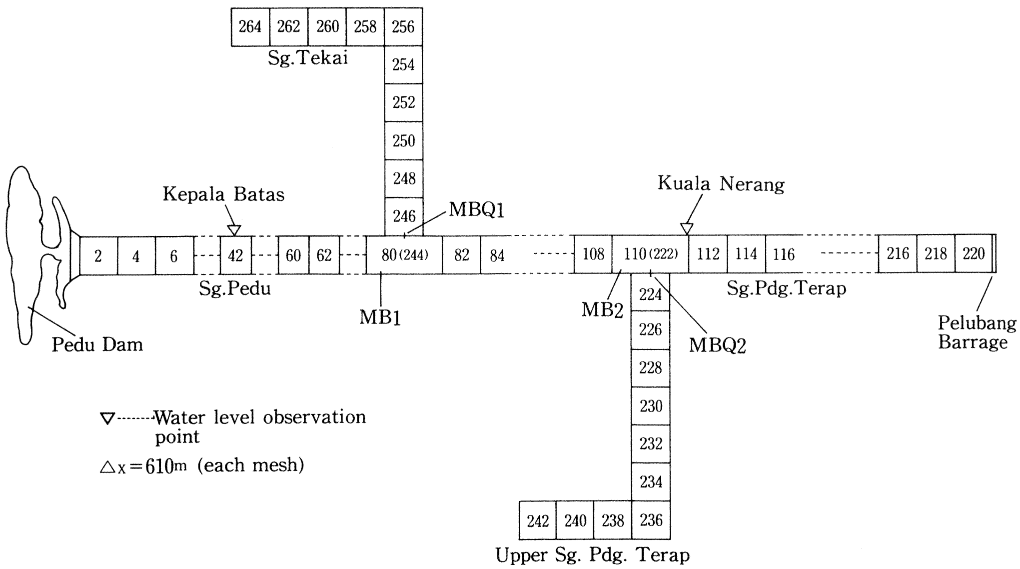


Fig.VI—6 Model structure of Sg. Padang Terap, Muda Scheme, Malaysia.

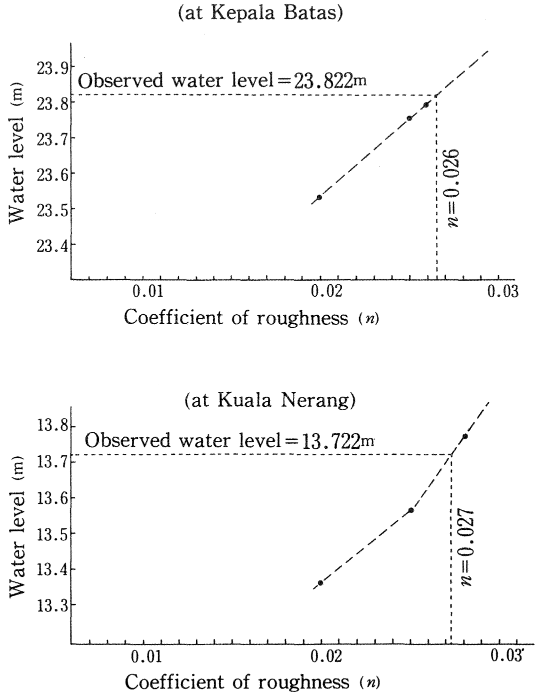


Fig. VI—7 Estimation of coefficient of roughness(n), Sg. Padang Terap, Muda Scheme, Malaysia.

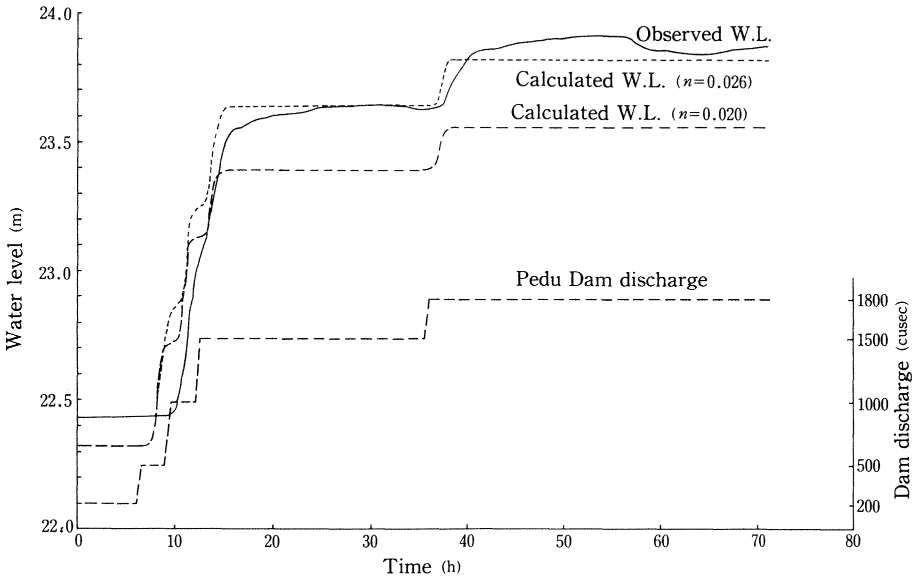


Fig. VI—8 Fluctuations of the water level at Kepala Batas ; 1986 dry season (Feb. 27, 1986 to Mar. 1, 1986), Muda Scheme, Malaysia.

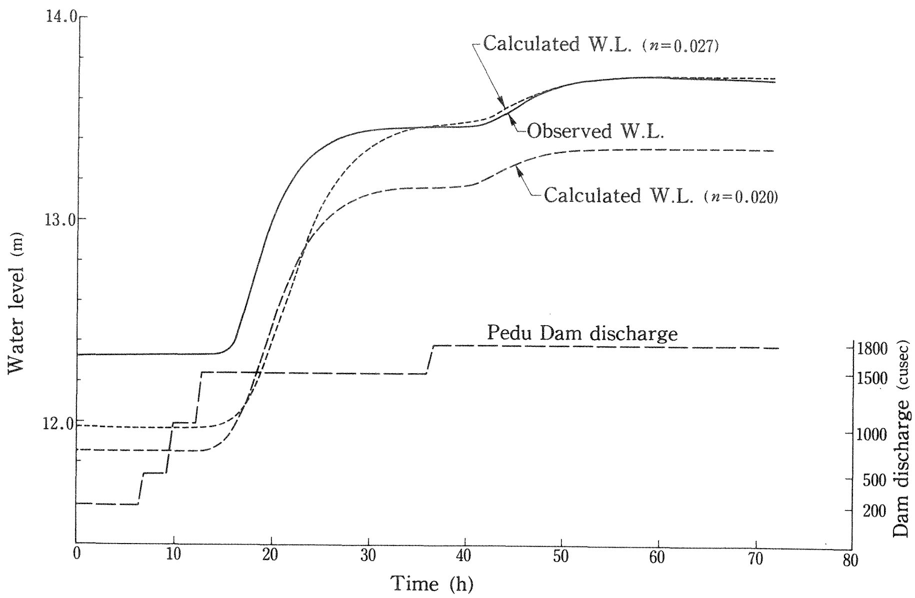


Fig. VI—9 **Fluctuations of the water level at Kuala Nerang ; 1986 dry season (Feb. 27, 1986 to Mar. 1, 1986), Muda Scheme, Malaysia.**

2.1.2 Analysis of flow-arrival time

(1) Estimation of coefficient of roughness

In order to construct a mathematical model that can reflect the actual flow conditions, it is necessary to estimate the coefficient of roughness (n) (or model coefficient) as accurately as possible. Based on the discharge data at the Pedu Dam and water level data at the Pelubang Headworks, Kuala Nerang and Kepala Batas stations collected during the early stage (Feb. 27-Mar. 1) of the 1986 dry season crop, the coefficient of roughness was estimated by the trial and error method as follows:-

Firstly, simulations were carried out by assuming a n value of 0.020 and 0.025 (whole reaches), 0.026 (upper reaches) and 0.028 (lower reaches). The computed water levels at the two stations were plotted against n as shown in Fig. VI-7, and the value of n that gave the observed water level was read. Therefore, n was estimated at 0.026 at Kepala Batas and 0.027 at Kuala Nerang. Figs. VI-8 and VI-9 show the water level fluctuations simulated by the model at both stations, of which n is 0.026 in the upper reaches (mesh No. 2-76) and 0.027 in the lower reaches (mesh No. 78-220), together with the observed data. It appears that the simulated results with the above n values agreed well with the observed data, and could be selected for subsequent analyses.

(2) Flow-arrival time

a) Method of investigation of the flow-arrival time and simulation cases

In this paper, the flow-arrival time is defined as the time required at a selected section for a canal system under steady flow conditions with a discharge Q to change to steady flow conditions with a discharge of $Q \pm \Delta Q$ when the upstream end discharge is increased by $\pm \Delta Q$. Therefore, under the initial conditions of steady flow and selected boundary conditions such as discharge at the upstream end and water level at the down-stream end, the simulation was continued until the appearance of steady flow conditions in the whole canal system covering a distance of 67km.

During the period when water release is required for the presaturation supply, the river flow from the basin is very small and negligible. Thus, only the dam release discharge was given as the boundary condition at the upstream end. For the boundary condition at the downstream end, the water level at the Pelubang Headworks (designed water level EL.8.02m) was given.

Firstly, the following two cases which differ in their initial conditions but show the same discharge increments are discussed.

Case 1…… initial steady flow of 5.0m^3/s, final steady flow of 33.3m^3/s (discharge increment of 28.3m^3/s)

Case 2…… initial steady flow of 28.3m^3/s, final steady flow of 56.6m^3/s (discharge increment of 28.3m^3/s)

The rate of discharge of 28.3m^3/s is equivalent to 1,000cusec (cubic feet per second) which is the discharge rate commonly used for water release operations at the Pedu Dam by MADA.

Then, another four cases, of which the discharge patterns at Pedu Dam are either in an increasing or decreasing process, are also discussed.

Case 3…… initial steady flow of 5.0m^3/s, final steady flow of 75.75m^3/s (discharge increment of 14.15m^3/s (500 cusec) at 3 hourly intervals)

Case 4…… initial steady flow of 75.75m^3/s, final steady flow of 5.0m^3/s (discharge increment of 14.15m^3/s at 6 hourly intervals)

Case 5…… initial steady flow of 5.0m^3/s, final steady flow of 56.6m^3/s (2000 cusec) (discharge increment of 51.6m^3/s was increased in 3 stages)

Case 6…… initial steady flow of 84.9m^3/s (3000 cusec), final steady flow of 56.6m^3/s (2000 cusec) (discharge increment of 28.3m^3/s (1000 cusec) was decreased in 3 stages)

The last four cases were set up for the investigation on the safety of the river canal as well as flow-arrival time under each water release pattern. Cases 5 and 6 are commonly encountered in the Muda Irrigation Scheme, and show a more practical water release pattern than Cases 3 and 4.

b) Flow-arrival conditions and non-dimensional expression

The water release pattern and the simulated discharge variations at Kuala Nerang (mesh No.110) and the Pelubang Headworks (mesh No.220) of Cases 1 and 2 are depicted in Fig. VI-10 which shows that when the initial discharge is larger, the flow-arrival time becomes shorter. It also shows that it is possible to estimate fairly accurately the discharge variations at the Pelubang Headworks by means of the simulation model. However, the model is not practical for studies on the flow-arrival conditions for every possible flow in a given canal system due to the large amount of time, effort and money involved. Therefore, a simplified estimation method of the flow-arrival conditions is required for optimising routine operations of the canal system.

The flow-arrival conditions in Cases 1 and 2 can be expressed by a non-dimensional curve (as proposed by Iwasaki [1981] whose abscissa is $t/(\Delta V/\Delta Q)$ and ordinate is $(Q_t - Q_b)/\Delta Q$ (= Q') as shown in Fig.VI-11. The non-dimensional curves obtained are compatible with the results reported by Iwasaki and they can be adopted for the estimation of the discharge variation and flow-arrival time at the Pelubang Headworks. Here, ΔV is the increment of water storage in the river (ΔV = 2.2 million cubic meter in Case 1, ΔV = 1.71 million cubic meter in Case 2), ΔQ is

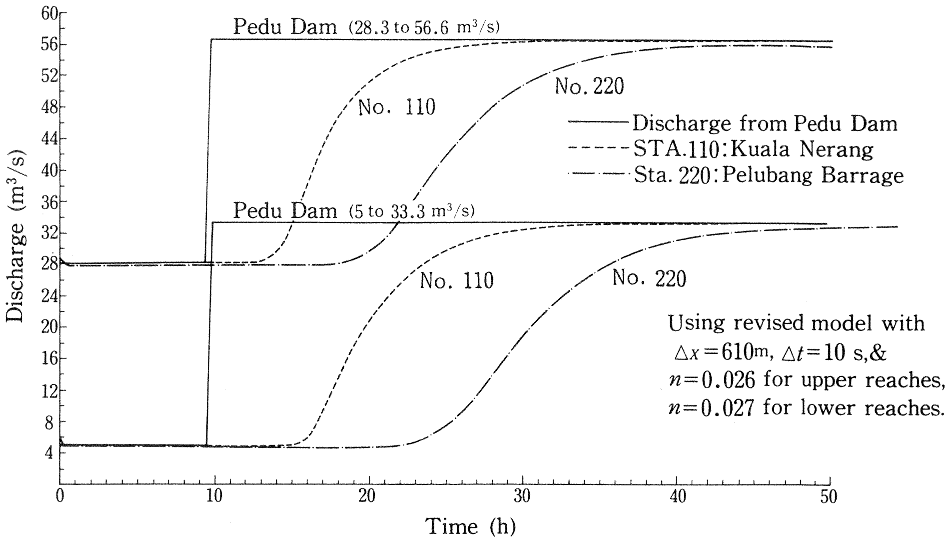


Fig. VI—10 Variations in the discharge at Kuala Nerang and Pelubang Headworks for ΔQ=1000cusec(28.3m³/s) depending on the initial discharge, Muda Scheme, Malaysia.

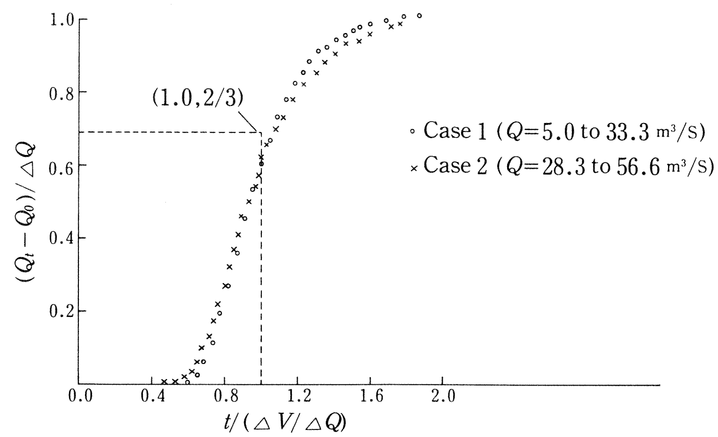


Fig. VI—11 Non-dimensional expression of arrival discharge at Pelubang Headworks (Cases 1 and 2), Muda Scheme, Malaysia.

the increment of discharge (= 28.3m³/s), Q_b is the initial discharge (Q_b = 5.0m³/s in Case 1, Q_b = 28.3m³/s in Case 2), and Q_t is the flow discharge at time t. By the application of the non-dimensional curve shown in Fig. VI-11, the flow-arrival time in the Muda Irrigation Scheme can be estimated. However, as shown in Fig. VI-11, two slight deviations from the existing information on the non-dimensional expression of the flow-arrival conditions were recognized as follows:-

① Based on the mathematical model simulation and on-site observations of various canal systems in Japan, Iwasaki proposed the following equation for the estimation of T_0. T_0 which is a non-dimensional value pertaining to $T_h = Le/(V_b + \sqrt{gh_b})$ depending on the velocity of waves corresponds to the time when the flow-arrival curve ascends.

$$T_0 = (Le/(V_b + \sqrt{gH_b}))/\frac{\Delta V}{\Delta Q} = T_h/\frac{\Delta V}{\Delta Q} \quad \cdots\cdots \text{(VI-8)}$$

where Le : canal length,
V_b : initial average velocity,
H_b : initial average water depth.

The values of the initial ascending points calculated by Eq. (VI-8) are (0.27, 0.0)

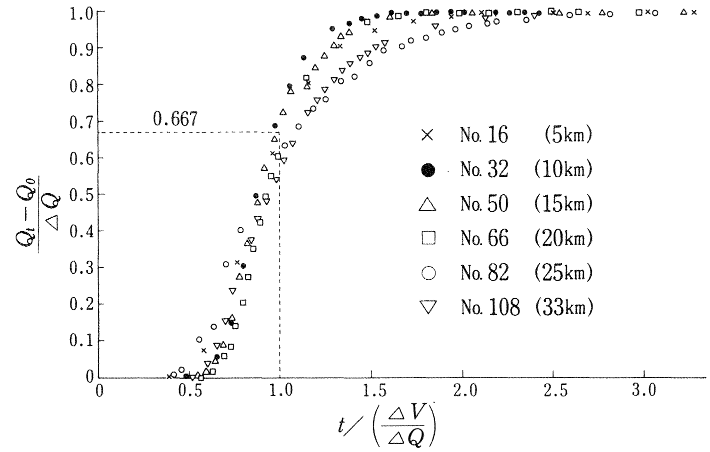


Fig. VI—12 Non-dimensional curves for flow-arrival at six points (Case 2 ; Q=28.3m³/s→ 56.6m³/s), Muda Scheme, Malaysia.

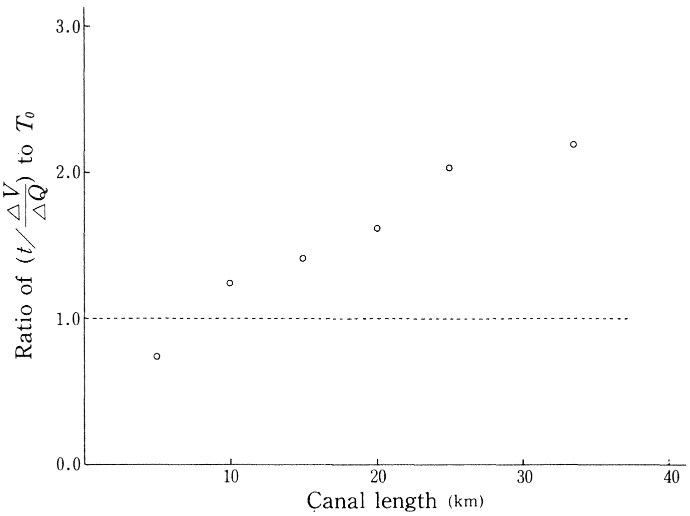


Fig. VI—13 Relationship between the canal length and the ratio of the initial ascending point of the non-dimensional curve to the calculated value of T_0.

in Case 1 and (0.20,0.0) in Case 2. However, the actual values of the ascending points obtained in Fig.VI-11 are (0.57,0.0) and (0.40,0.0) respectively, and do not coincide with the calculated values.

② Though Iwasaki pointed out that the non-dimensional curve should pass through the point (1.0,2/3), the actual ordinate values corresponding to the value 1.0 of the abscissa were slightly less than 0.667 (= 2/3) in the non-dimensional curves obtained.

By observing these deviations more closely, it may be possible to expand the generality of the non-dimensional expression of the flow-arrival time. Some proposals are presented as follows for consideration:-

Firstly, comments will be made on the initial ascending point of the non-dimensional curve. Eq.(VI-8) was proposed by Iwasaki based on the study carried out in irrigation canal systems with a length of less than 10km. For canal systems longer than 10km, the application of this equation has not been validated. Fig.VI-12 shows the non-dimensional curves for the flow-arrival at six points (five at every 5km from the Pedu Dam and one at Kuala Nerang which is located 35km downstream from the Pedu Dam). Table VI-4 and Fig.VI-13 show the relationship between the

Table VI—4 Comparison between calculated T_0 and initial ascending point of non-dimensional curve: Case 1 (Q=5.0m³/s → 33.3m³/s) (ΔQ=28.3 m³/s)

Points	Items						
	ΔV[1)] (1)	T_v[2)] (2)	T_h[3)] (3)	T_o[4)] (4)=(3)/(2)	$I.A.P$[5)] (5)	Ratio of (5) to (4) (6)=(5)/(4)	Remarks
	m³	h	h				
No. 16 (5 km)	7.104×10⁴	0.70	0.41	0.586	0.429	0.73	
No. 32 (10 km)	1.643×10⁵	1.61	0.81	0.503	0.621	1.23	
No. 50 (15 km)	2.843×10⁵	2.79	1.24	0.444	0.621	1.40	
No. 66 (20 km)	3.944×10⁵	3.87	1.61	0.416	0.67	1.61	
No. 78 (23.8 km)	4.785×10⁵	4.70	1.87	0.398	0.70	1.76	
No. 80 (24.4 km)	8.564×10⁵	8.41	1.92	0.228	0.42	1.84	confluence of Sg. Tekai
No. 82 (25 km)	8.770×10⁵	8.61	1.97	0.229	0.46	2.01	
No. 108 (33 km)	1.097×10⁶	10.77	2.51	0.233	0.49	2.10	
No. 110 (33.5 km)	1.567×10⁶	15.38	2.55	0.166	0.36	2.17	confluence of Sg. Pdg.Terap
No. 112 (34 km)	1.586×10⁶	15.57	2.60	0.167	0.41	2.46	
No. 220 (67 km)	2.206×10⁶	21.65	4.51	0.210	0.59	2.81	Pelubang Headworks

Notes:
1) ΔV=increment of river storage
2) $T_v=\Delta/\Delta Q$, ΔQ=increment of discharge
3) $T_h=L/(V_b+\sqrt{gh_b})$
4) T_o=non-dimensional value pertaining to T_h (=T_h/T_v)
5) $I.A.P$=the actual abscissa value of the initil ascending point ($t/(\Delta V/\Delta Q)$, 0)

canal length and the ratio of the values of initial ascending point of the non-dimensional curve to the calculated value of T_0. Based on this relation, the value of T_0 obtained by Eq. (VI-8) seems to correspond to the values of the ascending point of the non-dimensional curve within a 5-10km range for the canal length. The ratio tended to increase with the canal length. It is considered that the water flowing conditions in a canal system whose length exceeds 10km can be classified as 'mono-clinal rising wave' based on the classification of waves made by Kajisa et al [1986].

Therefore, the limit of application of Eq. (VI-8) corresponds to a canal length of about 10km. However, further studies should be carried out to develop methods of estimation of T_0 with wider application limits.

Secondly, while it has been reported that the non-dimensional curve should pass the point (1.0, 2/3) [Iwasaki 1981], in the non-dimensional curve obtained the ordinate value corresponding to the value 1.0 of the abscissa approached $Q' = 0.582$, which is the theoretical solution for uniform flow, proposed by Tamai and Iwasaki [1980]. This tendency was confirmed in Cases 1 and 2. Namely, for a canal system longer than 10km with storage functions such as tributaries, the non-dimensional curve tends to pass the point (1.0, 0.582) which corresponds to the theoretical solution of uniform flow.

Thirdly, the following information was obtained on the storage effect of rivers with tributaries. The tributaries with limited flow, but with a large storage capacity, act as regulating reservoirs and delay the flow-arrival time in the main river (Fig. VI-14). Based on the non-dimensional curves of the points located upstream and downstream of the confluence of the upper and lower tributaries in the main river, as shown in Figures VI-15 and VI-16, it is possible to study the impact of the storage effect of the tributaries upon the flow-arrival conditions. There was a considerable difference in the increment of the channel storage capacity in the main river at the confluence of the upper and lower tributaries. The increment of the channel storage capacity at the confluence of the upper tributary was $8.5 \times 10^5 m^3$ or about half of that at the confluence of the lower tributary ($16 \times 10^5 m^3$). Namely, the ratio of the increment of the channel storage capacity at the confluence of the tributaries to that in the main river was greater for the upper tributary than for the

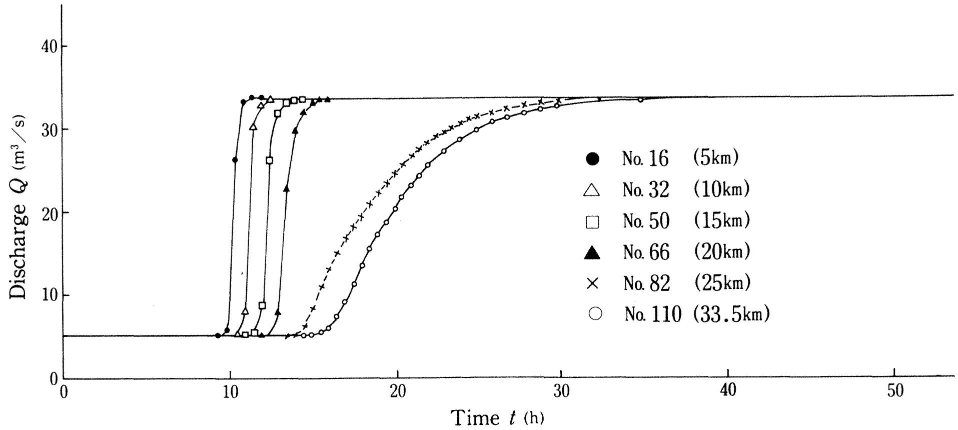


Fig. VI—14 Q—t curves at several points in main river (Case 1 ; Q =5.0m³/s → 33.3m³/s at t=9.5hours), Muda Scheme, Malaysia.

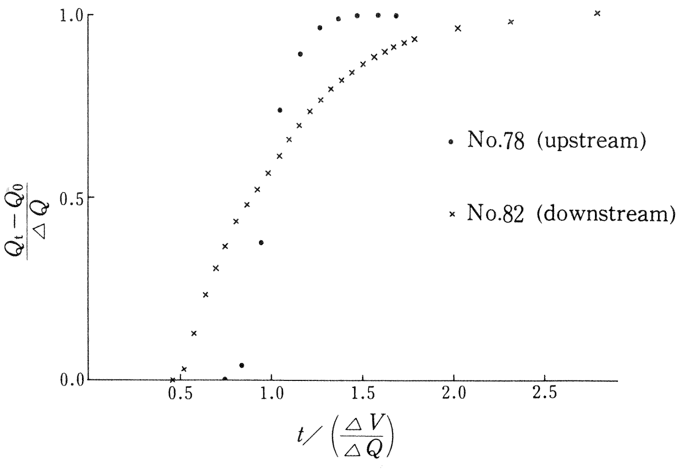


Fig. VI—15 Non-dimensional curves of points upstream and downstream at the confluence of the upper tributary (No. 80) (Case 1), Muda Scheme, Malaysia.

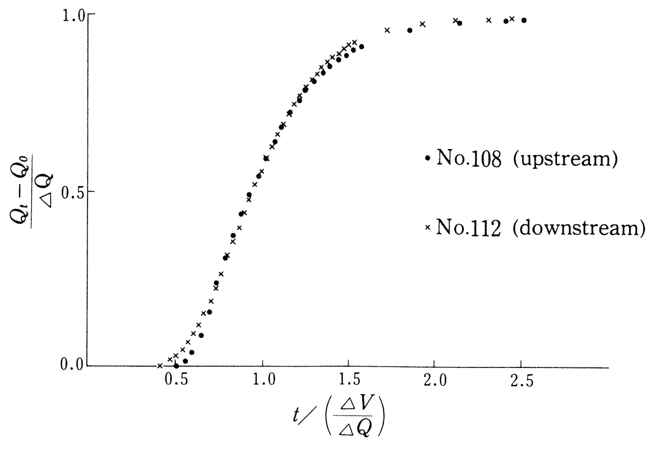


Fig. VI—16 Non-dimensional curves of points upstream and downstream at the confluence of the lower tributary (No. 110) (Case 1), Muda Scheme, Malaysia.

lower tributary. Therefore, the difference in the non-dimensional curve between the upstream and downstream areas at the confluence of the upper tributary was more significant than that of the lower tributary. It is evident that the storage effect of tributaries exerts a significant effect on the pattern of the non-dimensional curve.

c) Flow-arrival conditions and non-dimensional expression for step-by-step release pattern

Other simulations were carried out for the "step-by-step release pattern", of which discharges were increased (or decreased) in several stages such as in Cases 3~6, by using the same mathematical model. In order to investigate the storage effect of

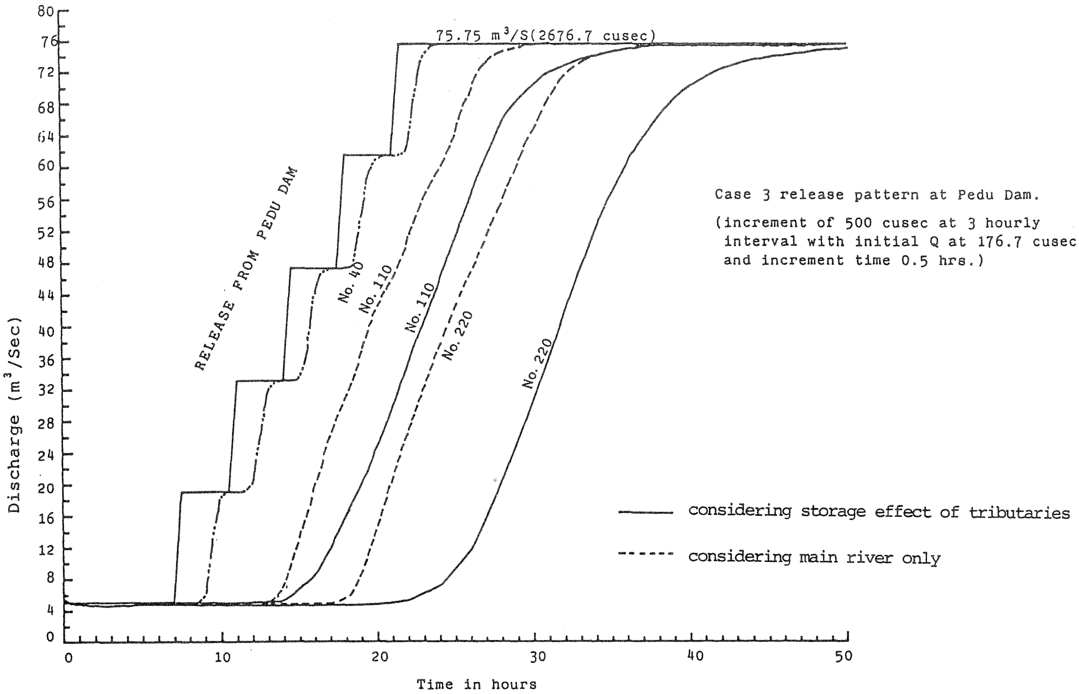


Fig. VI—17 Discharge variation at several points calculated by two Models (Case 3 release pattern), Muda Scheme, Malaysia.

tributaries, another model including only the main river but excluding its tributaries was prepared.

The patterns of discharge variation at several stations in Case 3 are shown in Fig. VI-17. Discharge variations at Kuala Nerang (mesh No. 110) and Pelubang (mesh No.220) were calculated by using both models. In this figure, the discharge at mesh No.40 located 12 km downstream from the Pedu Dam varies in stages in accordance with the pattern of discharge from the dam, but it changes gradually at mesh Nos. 110 and 220. Namely, as the discharge increases very rapidly in the upper reaches in Case 3, it is desirable for the safety of the local inhabitants to set up a warning system along the river for the water release from the dam. From this figure, the magnitude of the storage effect of the tributaries is evident when the discharge variations at meshes Nos.110 and 220 calculated by two models are compared. Water profiles under steady conditions at 0 hr. and 45 hr. for Case 3 are shown in Fig.VI-18.

The pattern of discharge variation at several points calculated by both the models in Case 4 are shown in Fig.VI-19. In case of the calculated results by the model excluding the tributaries, the wave profile of the reservoir release is transmitted up to meshes Nos.110 and 220. However, in case of the results calculated by the model including the tributaries, the waves almost disappear at the same points because of the storage effect of the tributaries. The discharge at mesh No.40 (12 km downstream from the Pedu Dam) varies in stages in accordance with the dam discharge pattern and decreases suddenly. Therefore, some proper measures should be taken against

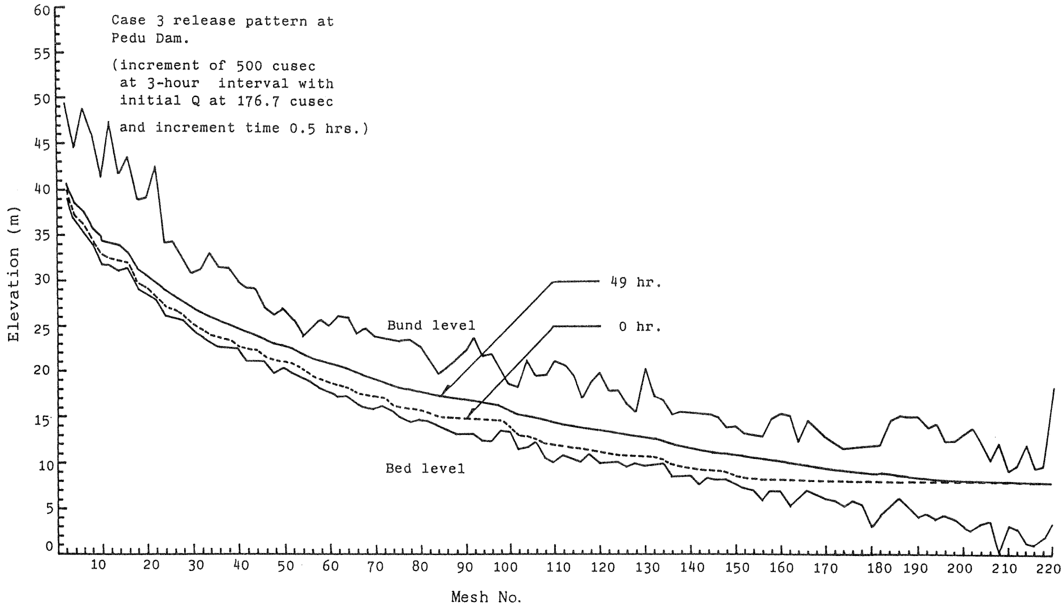


Fig. VI—18 Water profile at steady condition at 0 hr. and 49 hr. (Case 3).

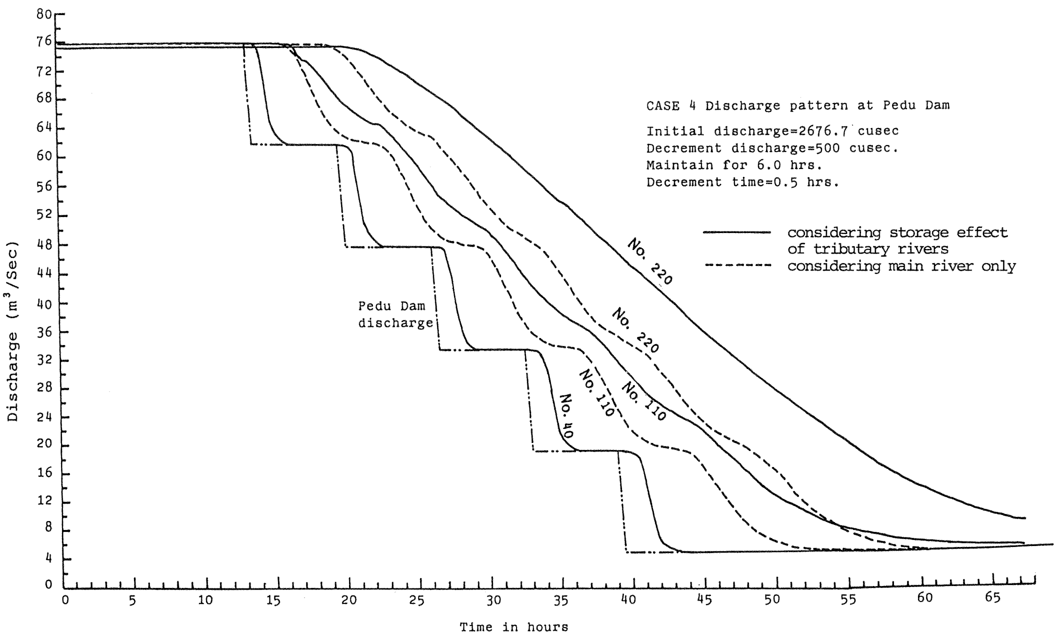


Fig. VI—19 Discharge variation at several points calculated by two Models (Case 4 release pattern), Muda Scheme, Malaysia.

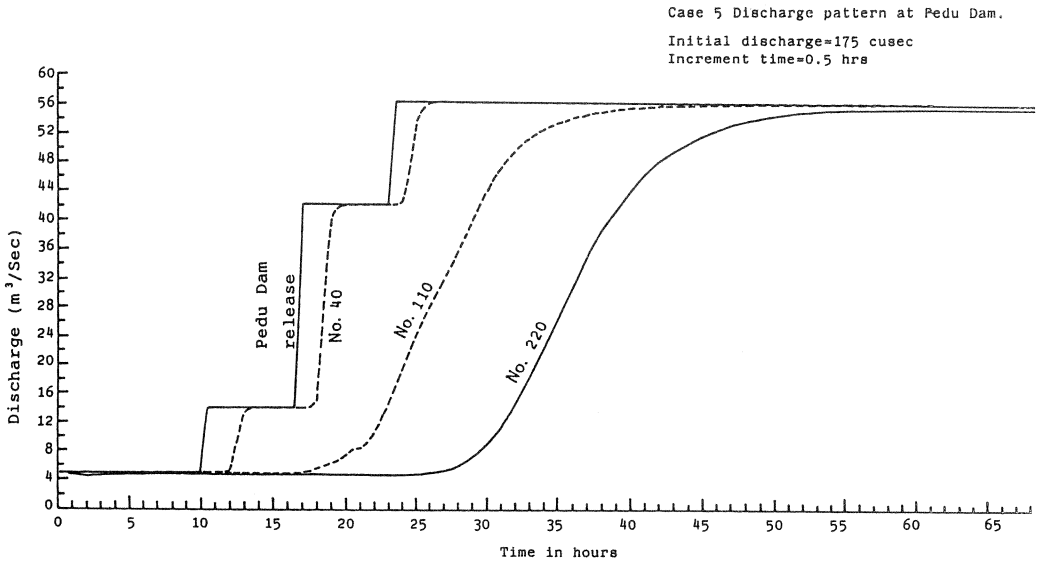


Fig. VI—20 Discharge variation at several points (Case 5), Muda Scheme, Malaysia.

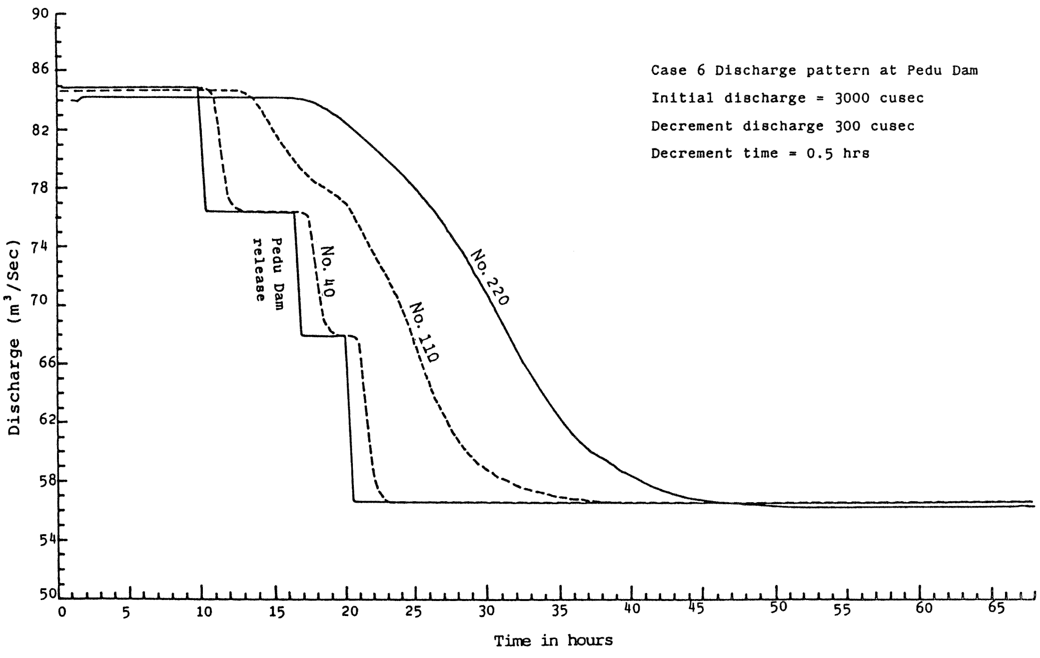


Fig. VI—21 Discharge variation at several points (Case 6), Muda Scheme, Malaysia.

the slope failure of the river levees due to the sudden drop of the water level in the upper reaches.

The patterns of discharge variation at several points in Cases 5 and 6 are shown in Figs. VI-20 and VI-21 respectively. The results of Cases 5 and 6 showed similar tendencies to those of Cases 3 and 4 respectively.

It was demonstrated that T_v (= $\Delta V/\Delta Q$) for the "step-by-step release pattern" can be expressed as follows (Fig. VI-22) [Yoshino eq al. 1986] :-

$$T_v = \frac{\triangle V - \{\sum_{i=1}^{n-1} \triangle Q_i (t_{i,1} - t_{i-1,1}) - \frac{1}{2}\sum_{i=1}^{n} (\triangle Q_i - \triangle Q_{i-1})(t_{i-1,2} - t_{i-1,1})}{\triangle Qn} + t_{n-1,1} \quad \cdots\cdots\cdots \text{(VI-9)}$$

Here, $\Delta Q_0 = 0$, $t_{0,1} = 0$, $n \geqq 2$

In case $t_{i,1} = t_{i,2}$, T_v is expressed as follows:-

$$T_v = \frac{\Delta V - \sum_{i=1}^{n-1} \Delta Q_i (t_{i,1} - t_{i-1,1})}{\Delta Q_n} + t_{n-1,1} \quad \cdots\cdots\cdots \text{(VI-10)}$$

Namely, T_v is equal to the time when the volume of inflow water becomes equal to the increment of storage water (= ΔV) in a river.

In Case 5, the flow-arrival time (T) was calculated by Eq. (VI-10) as follows:-

$$T = \frac{3,585,000 - (9.1 \times 6.5 \times 3600 + 37.4 \times 6.5 \times 3600)}{51.6} + 13.0 \times 3600$$

$$= 95,190 \text{ sec} = 26.4 \text{ hours}$$

In Case 3, T was similarly estimated at 90,002 seconds, namely 25.0 hours. The flow-arrival conditions for Cases 3 and 5 can be expressed by non-dimensional curves

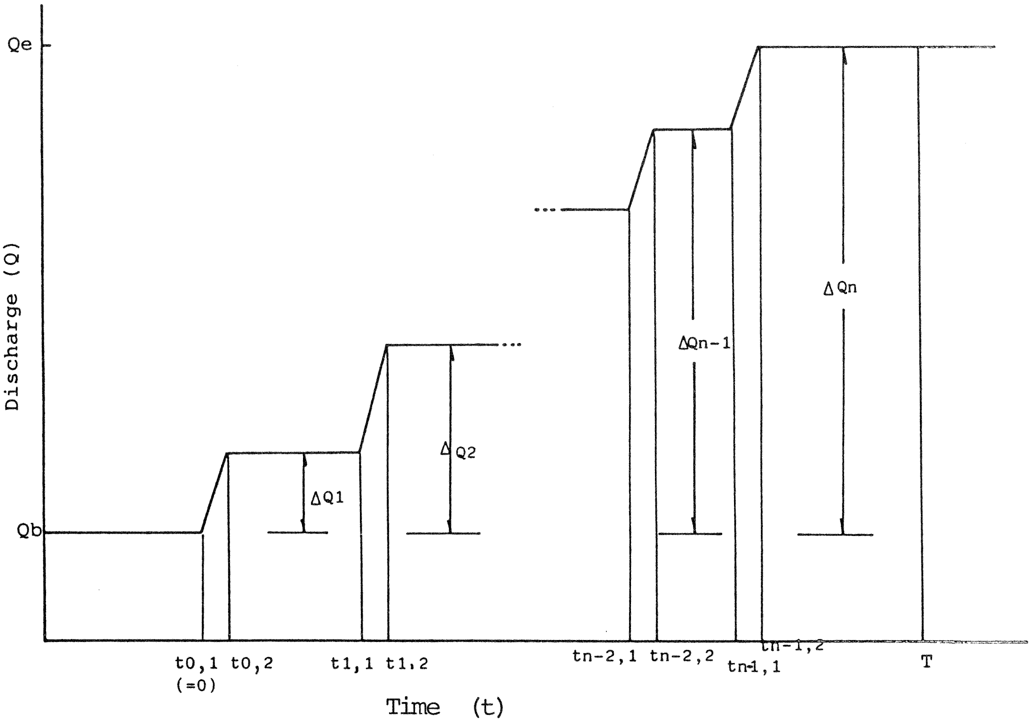


Fig. VI—22 Expression of Eq. (VI-9).

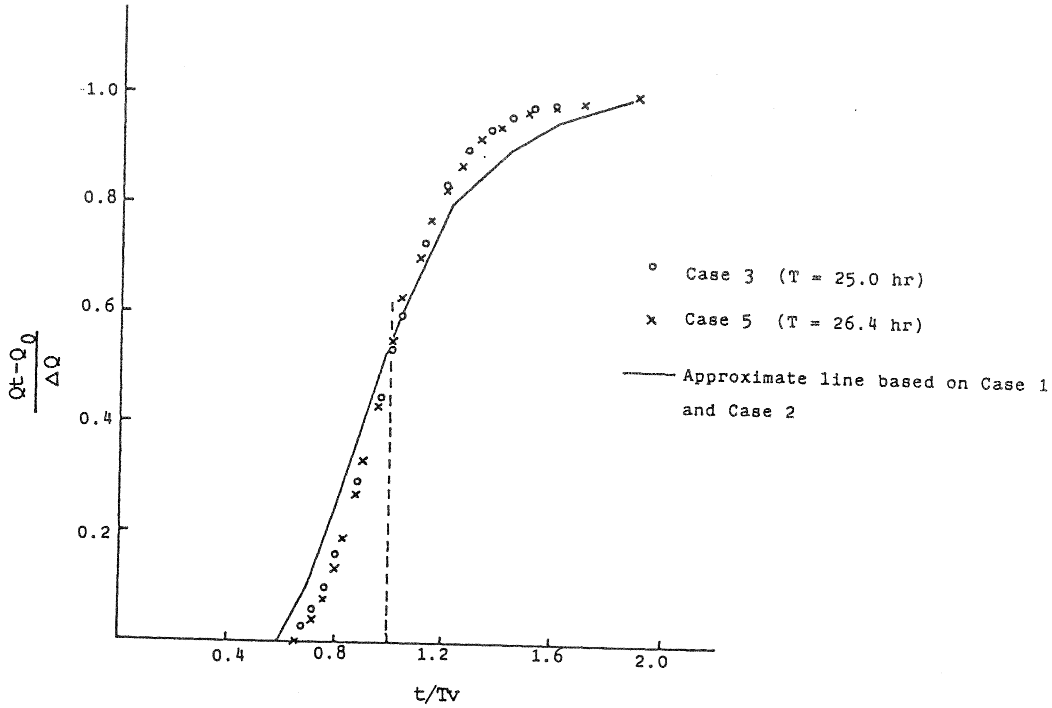


Fig. VI—23 Non-dimensional expression of arrival discharge at Pelubang Headworks, Muda Scheme, Malaysia.

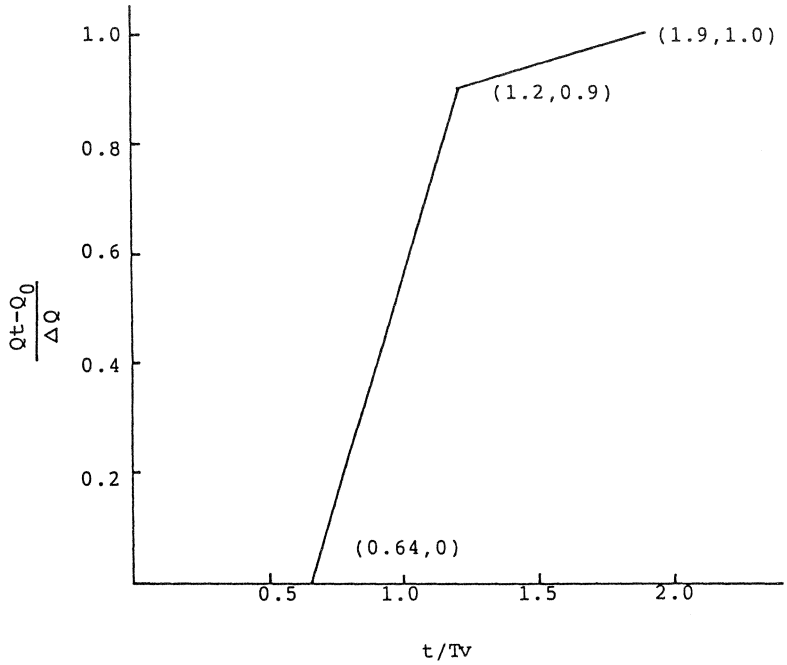


Fig. VI—24 Simplified non-dimensional curve of arrival discharge at Pelubang Headworks for the step-by-step release pattern from Pedu Dam, Muda Scheme, Malaysia.

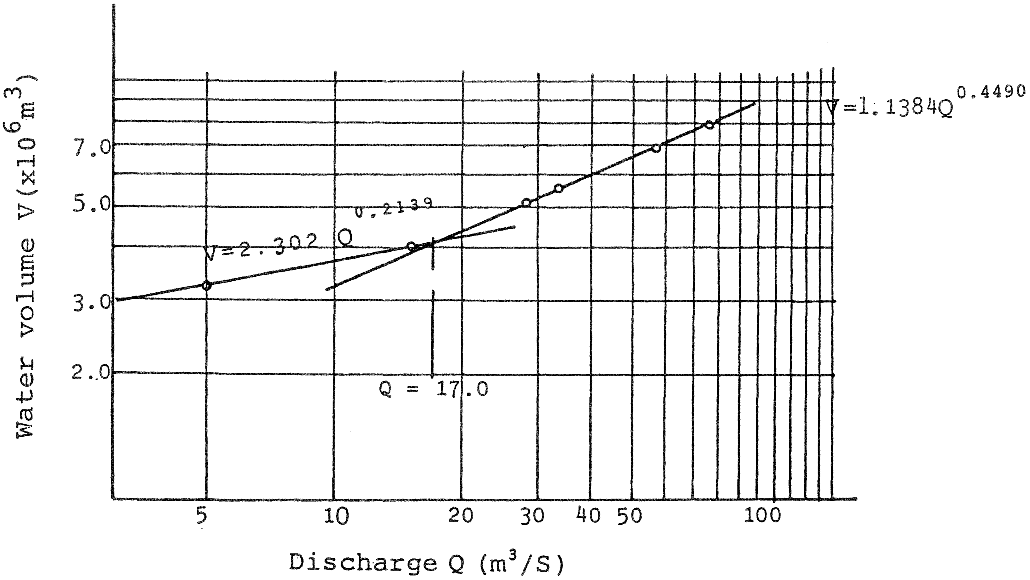


Fig.VI—25 Relationship between discharge and water volume from Pedu Dam to Pelubang Headworks, Muda Scheme, Malaysia.

as shown in Fig.VI-23. Non-dimensional curves for Cases 3 and 5 are almost the same. In comparison with approximate curve based on two non-dimensional curves for Cases 1 and 2, in the curves for Cases 3 and 5, the appearance of the initial ascending point is comparatively delayed and the point is slightly higher in $(Q_t-Q_0)/\Delta Q$ when t/T_v is 1.2-1.8. However, the non-dimensional curves for Cases 3 and 5 also pass almost the same point (1.0,0.582), which corresponds to the theoretical solution of uniform flow, as the approximate curve. The non-dimensional curves for Cases 3 and 5 seem to be more practical for the actual operations than those for Cases 1 and 2, and can be simplified as shown in Fig.VI-24.

It is considered that the simplified non-dimensional curve can be used for the practical management of the conveyance system in the Muda Irrigation Scheme. Moreover, the relationship between the water volume and discharge from Pedu Dam to Pelubang Headworks can be obtained by Fig.VI-25 or the following equations.

$$\begin{aligned} V &= 1.1384Q^{0.4490} \quad (Q \geqq 17.0\,m^3/sec) \\ V &= 2.302Q^{0.2139} \quad (Q < 17.0\,m^3/sec) \end{aligned} \quad \cdots\cdots\cdots \text{(VI-11)}$$

By using the non-dimensional curve obtained and the above equations, the discharge variation at the Pelubang Headworks can be estimated. For example, when the release discharge from the dam is increased from 45.914m^3/s to 71.264m^3/s in two stages as shown in Fig.VI-26, the discharge variation at the Pelubang Headworks can be summarized as follows [Yoshino et al. 1986] :-

Q (m^3/s)	ΣV (m^3)	ΔV (m^3)	$T = \frac{\Delta V - \Delta Q_1 t_1}{\Delta Q_2} + t_1$ (hour) $t_1 = t_2 = 4$ hours	$T_0 = 0.64T$ ($Q' = 0.0$)	$T_1 = 1.2T$ ($Q' = 0.9$)	$T_2 = 1.9T$ ($Q' = 1.0$)
45.914	6,346,000		$\Delta Q_1 = 14.086$			
		1,385,000	$\Delta Q_2 = 25.350$	10.8	20.3	32.2
71.264	7,731,000		$T = 16.95$		($Q = 68.729$)	

Then, the discharge variations can be estimated as shown in the following figure.

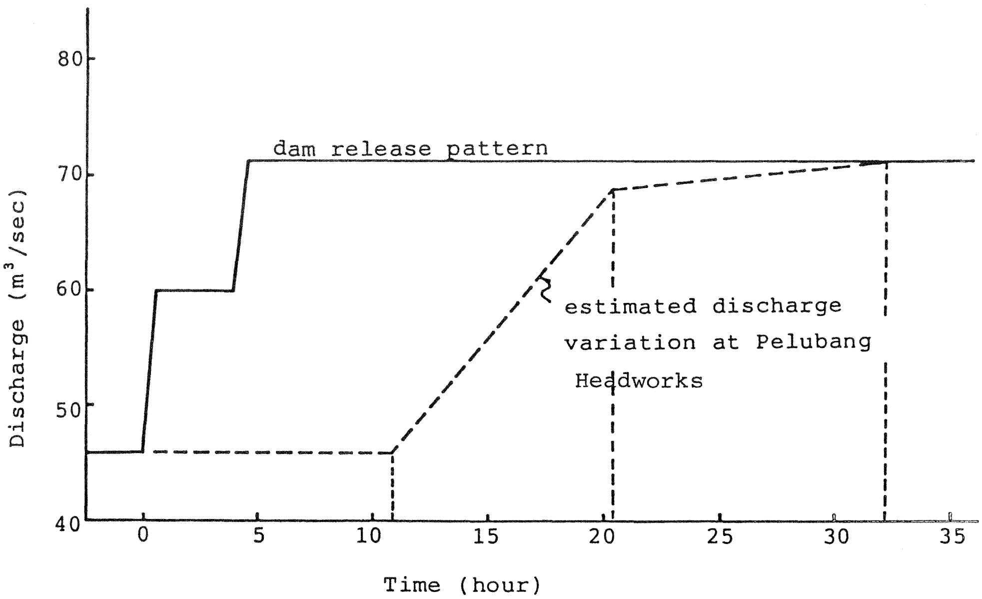


Fig. VI—26 Estimated discharge variation at Pelubang Headworks, Muda Scheme, Malaysia.

2.2 Conclusions

The flow-arrival time was investigated in the conveyance system in the Muda Irrigation Scheme based on a mathematical model simulation. The results of a series of analyses are summarized as follows:-

① The applicability of Eq. (VI-8) to the initial ascending point of the non-dimensional curve is limited. The maximum canal length for the application of this equation seems to be approximately 10km.

② In the non-dimensional curve the ordinate value corresponding to the value 1.0 of the abscissa tends to approach to $Q' = 0.582$ which is the theoretical solution of uniform flow obtained by Tamai et al [1980] for the canal length.

③ Tributaries show a storage function comparable to that of a regulating reservoir and affect the non-dimensional curve. However, the effect depends on the ratio of the increment or decrement of the channel storage capacity of the tributaries to that of the main river.

④ The flow-arrival conditions at the Pelubang Headworks of any water release pattern from the Pedu dam can be estimated easily by using the simplified non-dimensional curves (Figs. VI-23 and VI-24) and the relationship between the water storage in the river canal and the released discharge from the dam (Eq. (VI-11) or Fig. VI-25).

⑤ In the upper sections of the river canal, a warning system should be equipped for the safety of the local inhabitants against a sudden increase of the water level due to the onset of water release from the dam, and some proper measures should be taken against the slope collapse of the river levees caused by the sudden decrease of the water level due to the discontinuation of water release from the dam.

3. Problems and measures to improve the management of the distribution system

In the dry zone area of Sri Lanka, effective macroscopic water utilization had been achieved for a long time by linking a large number of tanks together in a river basin. It is, however, difficult to assume that water is effectively utilized in areas depending on each individual tank, because water diversion is not uniform and shows considerable variations in quantity in the main as well as distributary (secondary) canals.

In the Muda Scheme, all the diversion works (offtakes) are standardized by the use of over-shot type gates or CHO (Constant head orifice; double orifice) type gates, which make provision for metering the discharge. However, there are some problems in the operation and maintenance of the distribution system due to insufficient consideration of the flow-arrival time and other hydraulic phenomena in the system.

In this chapter, actual status of water diversion in the existing systems was clarified, and some aspects which should be considered for improving the management of the distribution system were discussed based on on-site experiments.

3.1 Problems in the dry zone area of Sri Lanka

In the dry zone area of Sri Lanka, the gate-controlled diversion works are commonly adopted in the distribution system. Fig. VI-27 shows a typical structure of the gate-controlled diversion works which make no provision for metering discharge. Normally, gates are made of wood resulting in water leaks. Gate-opening can be adjusted manually only in limited stages. The screw-spindle type gates, of which the opening can be adjusted continuously, are normally used only for the large diversion works supplying a wide area. In a large-scale irrigation scheme, the diversion works are maintained and operated by the control office under the Irrigation Department, and the gates are locked so that they can not be operated by the farmers without permission. Gate-opening of the diversion works is decided daily based on the storage capacity of the tank (reservoir), the stage of plant growth and the weather conditions in the command area, and the gates are operated by a waterman who receives instructions from the head of the office.

For example, in case water shortage is anticipated due to the insufficient storage capacity of a tank, intermittent irrigation is substituted for continuous irrigation which is adopted under ordinary conditions. Then, operation plans for all the diversion works are set up based on intermittent irrigation and proper instructions are given to the waterman.

Though the gate operation of the diversion works is carried out fairly well by the waterman, comparatively large scattering in the water distribution among the

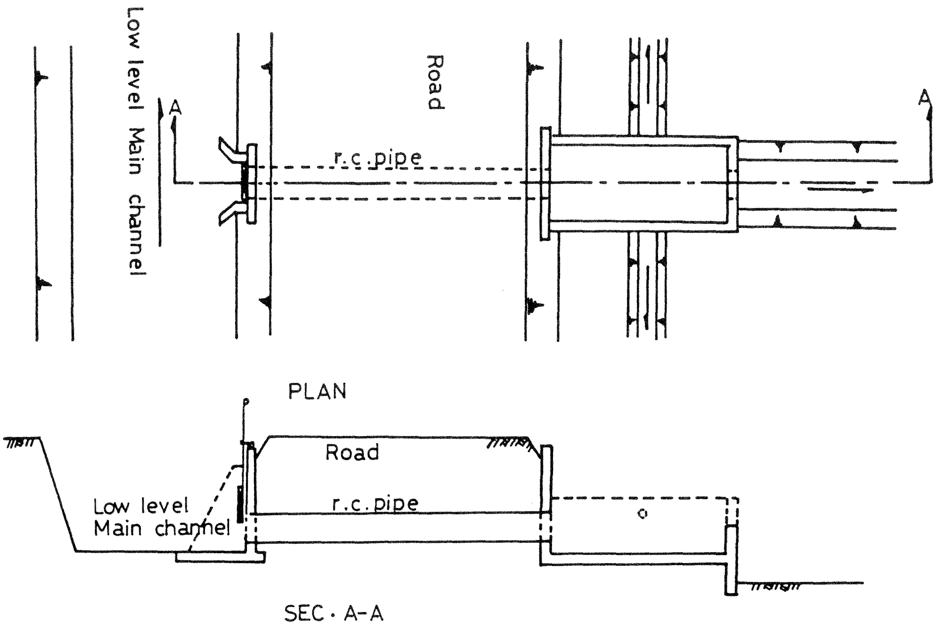


Fig. VI—27 Gate-controlled diversion works, Rajangana Scheme, Sri Lanka.

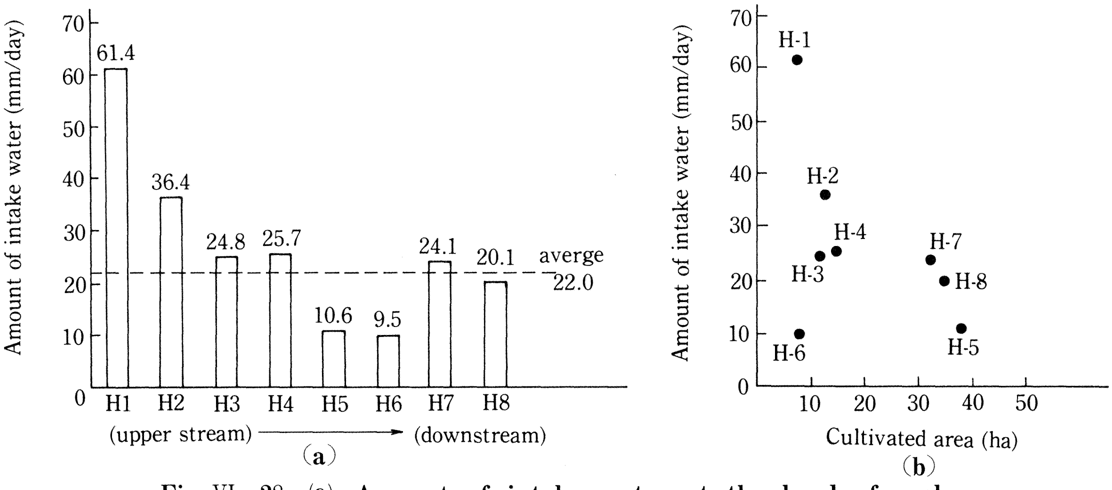


Fig. VI—28 (a) **Amount of intake water at the head of each distributary channel**

(b) **Relationship between amount of intake water and cultivated area**

(Jan. 10-11, 1980 Maha), High Level Main Channel, Nachchaduwa Scheme, Sri Lanka

diversion works was observed in the secondary canals as well as the main canals. Fig. VI-28 shows the amount of intake water per unit area at the head of the diversion works in the High Level Main Channel in the Nachchaduwa Scheme, which was observed during the period when the water movement in the area was comparatively steady. In order to clarify the relationship between the amount of intake water per unit area and the location of the diversion works, both simple regression and multiple regression analyses were performed by using actual data obtained from the three irrigation schemes. The results are shown in Tabel VI-5, and the following trends were confirmed.

1) Diversion works located upstream of the main and secondary canals take in a large quantity of water per unit area in comparison with those located downstream (Fig. VI-28(a))

2) Diversion works commanding a small area take in a larger quantity of water per unit area than those serving a large area (Fig. VI-28(b))

3) In the Mahakanadarawa Scheme, the ratio of cultivated area to the total area benefiting from irrigation under each diversion work shows a comparatively high negative correlation with the quantity of intake water per unit area through the diversion works. Namely, the quantity of intake per unit area tends to increase with the decrease of the cultivation ratio in the area benefiting from irrigation.

3.2 Primary factors causing the above trends in water diversion

In this paragraph, the primary factors causing the above three trends were investigated.

Table VI—5 Correlation between amount of diversion-water and some factors of diversion works

Scheme name	Cultivation season	X1[1]	X2[2]	X3[3]	X4[4]	X5[5]	Multiple regression formula Y[6]
Mahakanadarawa	R.B '74 Maha	③(0.191)	④(0.138)	②(−0.492)	⑤(−0.067)	①(−0.879)	Y= 52.17−30.35X5−0.0630X3−0.435X2
	'76/77 Maha	③(−0.218)	③(−0.106)	①(−0.323)	②(−0.230)	④(−0.161)	Y= 29.19−0.0970X3−0.546X1
	L.B '74 Maha	①(−0.540)	②(−0.533)	③(−0.430)	④(−0.401)	⑤(−0.281)	Y= 21.78−0.789X1−0.0439X3
Nachchaduwa	H.L '76/77 Maha	——	②(−0.620)	①(−0.648)	——	——	Y= 26.87−0.389X3
	'79/80 Maha(1) (20-12-1979)	——	①(−0.822)	②(−0.564)	——	——	Y= 82.81−9.46X2
	'79/80 Maha(2) (9-1-1980)	——	①(−0.648)	②(−0.431)	——	——	Y= 96.99−13.03X2
	'79/80 Maha(3) (10-1-1980)	——	①(−0.727)	②(−0.471)	——	——	Y= 48.63−4.90X2
Rajangana	R.B '79/80 Maha(1) (13-12-1979)	①(−0.594)	——	②(−0.297)	——	——	Y= 30.38−0.921X1−0.0085X3
	'79/80 Maha(2) (18-1-1980)	①(−0.724)	——	②(−0.204)	——	——	Y= 31.64−1.10X1−0.0080X3
	L.B '79/80 Maah(1) (14-12-1979)	①(−0.327)	——	②(−0.257)	——	——	Y=36.54−0.486X1−0.0078X3
	'79/80 Maha(2) (29-11-1979)	②(0.220)	——	①(−0.463)	——	——	Y= 45.85−0.0333X3
	'79/80 Maha(3) (17-1-1980)	①(−0.650)	——	②(−0.317)	——	——	Y= 36.61−0.657X1−0.0040X3

Notes : 1) X1 : mileage of diversion works reckoned from head gate of reservoir (km)
2) X2 : turn of diversion works reckoned from head gate of reservoir
3) X3 : cultivated area under diversion works (ha)
4) X4 : entire benefited area under diversion works (ha)
5) X5 : X3/X4
6) Y : amount of diversion-water (mm/d)

1) The first trend is due to the considerable difference between the actual coefficient of roughness of the canal and the designed one. As the value of the actual coefficient of roughness is larger than the designed one, the actual surface slope of a canal is steeper than the designed one. Namely, diversion works located upstream can easily take in a larger quantity of water due to the hydraulic gradient between the canal and its branch canal. Accordingly, diversion works located downstream receive a smaller quantity of water.

The actual coefficients of roughness observed in the main canals of the Rajangana Scheme were as follows:-

① L.B. Main channel (earth canal) ························0.052
② R.B. Main channel Br. 2 (earth canal) ···············0.038
③ R.B. Main channel Br. 3 (earth canal) ···············0.037

Meanwhile, the designed coefficients of roughness adopted by the Irrigation Department are as follows:-

(a) Concrete lining canal ··························0.015
(b) Concrete block lining canal ···················0.018
(c) Earth canal ·····································0.025
(d) Natural river ··································0.035

While the designed coefficient of roughness was 0.025, the actual coefficients of roughness for the existing canals in the Rajangana Scheme were far larger and even larger than the designed value for a natural river. The increment of the roughness of the canals is due to the overgrowth of aquatic plants and weeds as well as the stagnation of driftwood and rubbish. To secure an even distribution of water, the coefficient of roughness should be maintained at the designed level by appropriate management. Such a trend in unevenness in water distribution associated with the differences in elevation head among diversion works in the same canal system can be compensated by appropriate gate operations in each diversion work. However, in almost all the diversion works there are water leaks associated with the presence of wooden and old gates and gate-opening can be adjusted only in limited stages. Accordingly, the quantity of water distributed through each diversion work depends very much on the elevation head (command) at each point.

2) The second trend is due to the relationship between the gate structure of the diversion works and the command area. Generally, when the command area is large, the diversion works are designed using either screw-spindle type gates which can be adjusted continuously or other types of gates which can be adjusted in various stages. However, in a small command area, almost all the diversion works can be adjusted only in 3~4 stages.

Fig. VI-29 shows an example of the relationship between gate-opening and water discharge in a diversion work controlled by a small gate with a command area of 72.9ha in the R.B. Main Channel of Rajangana Scheme. This diversion work can be adjusted only in 4 gate-opening stages. In such a case, it is necessary to set the gate at two-thirds (2/3) of its full opening for a water diversion amounting to 0.15m³/sec. However, in this case 0.21m³/sec is diverted to the command area instead of 0.15m³/sec.

To secure an even distribution of water, all the diversion works should be improved in order that the gate-opening is adjusted continuously.

3) The third trend is due to the lack of flexibility of the distribution canal in supplying a small discharge below designed discharge. The diversion works and distribution canals are originally designed so as to cover a whole command area.

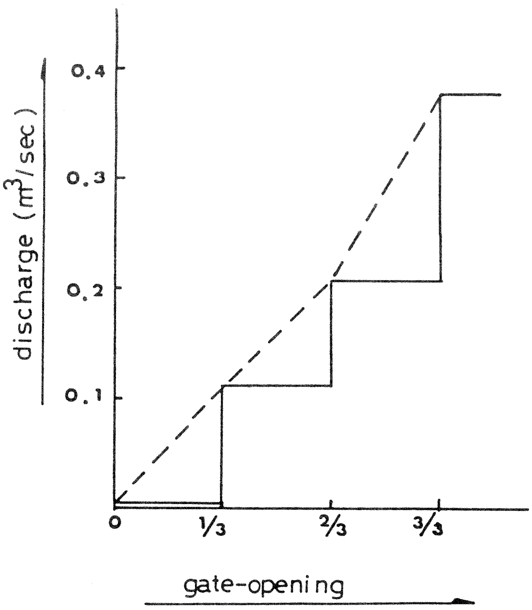


Fig. VI—29 **An example of the relationship between gate-opening and its discharge in a small gate-controlled diversion works, R.B Main Channel, Rajangana Scheme, Sri Lanka.**

Therefore, when the cultivated area is temporarily decreased due to drought, it is very difficult to distribute and supply the proper discharge which corresponds to the cultivated area.

The difficulty in the even distribution of water for an area with a low cultivation rate is due more to the structure of the distribution canal than to the diversion works in which the adjustment of gate-opening may be difficult. Even if the proper amount of discharge corresponding to the cultivated area is distributed through the diversion works, there are frequent instances when the distribution canal does not function well in supplying water to the paddy fields. Namely, the decreased water level due to decreased discharge makes the water supply to paddy fields difficult. Accordingly, in order to supply the water to the terminal paddy fields, it is necessary to take in excess water (referred to as maintenance water requirement), through the diversion works to maintain the hydraulic gradient between the distribution canal and fields. The ratio of water requirement for maintenance to the total amount of water distributed to the canal increases with the reduction of the cultivation rate in the command area. This situation aggravates the irrigation disputes among the diversion works. As a result the diversion works upstream of the canals take in a large quantity of water in comparison with those located downstream.

To alleviate this shortcoming, regulators such as stop-logs should be set at proper points in the distribution canal in order to keep the water level high enough to supply the water to the paddy fields and to take in a proper quantity of water from the diversion works. However, as even in the parent canal the water level decreases during the drought, water diversion becomes difficult due to the insufficient elevation head. It is desirable to set regulators in the parent canal, too. In such a case the operation and maintenance systems should be well defined, otherwise the diversion works located upstream of the canals will take in a large quantity of water.

3.3 Some aspects in the distribution system in the Muda Scheme

In the Muda area, usually one operator is in charge of operating a major structure such as regulator and diversion work. The gate operation of each structure is performed every four hours in the daytime, i.e. 7.00 a.m., 11.00 a.m., and 3.00 p.m. [MADA 1977]. It seems that there are two problems in this operation rule. One is the coincidence of the operation time in the entire Muda area, the other is the short interval, i.e. only four hours between the operation time. If all the irrigation structures are simultaneously operated in the entire Muda area, the flow of all the canal system changes to an unsteady condition instantaneously. In this case, even if the gates are adjusted for the required discharge at each structure, the discharge changes immediately far from the originally adjusted discharge. Therefore, it is important to manage irrigation structures in due consideration of the locational relations of all the structures and flow-arrival time in a series of conveyance and distribution system. It frequently takes more than four hours for the flow to become steady after the gate adjustment.

Based on simulations of the gate operation of the regulators in the Northern Canal, when the flow passes over the gate under the condition of perfect overflow, the water level and the discharge become steady in a comparatively short time (within three hours). However, when the flow at the gate is under a submerged condition, it takes five or six hours for it to become steady. Accordingly in such a case, the next gate operation will be performed under unsteady flow conditions. The interval between the gate operations should be determined after due consideration based on a large number of simulation analyses. In each structure, the flow condition should be considered as well as the flow-arrival time for determining the time and interval of operations.

3.4 Conclusions

The results of a series of investigations on the distribution system based on on-site experiments are summarized as follows:-

① Diversion works located in upstream of a canal tend to take in a large quantity of water per unit area. This is due to the actual coefficient of roughness for the existing canals which is far larger than the designed value and even larger than the designed value for a natural river. To secure an even distribution of water, the coefficient of roughness should be maintained at the designed level by appropriate management.

② Diversion works commanding a smaller area take in a larger quantity of water per unit area than those supplying a larger area in the dry zone of Sri Lanka. This trend is due to the structure of the small diversion works of which the gate-opening can be adjusted only in limited stages. For impartial water distribution, all the diversion works should be improved in order that the gate-opening is adjusted continuously.

③ The quantity of intake water per unit area through the diversion works tends to increase with the decrease of the cultivation ratio in the area benefiting from irrigation. This is due to the lack of flexibility of the distribution canal in supplying a small discharge below designed discharge. To alleviate this shortcoming, regulators such as stop-logs should be set at proper points in the distribution canal in order to keep the elevation head high enough to supply the water to the paddy fields.

④ In a large irrigation scheme such as the Muda Scheme, it is very important to manage the irrigation structures in due consideration of the locational relations of all the structures and flow-arrival time in a series of distribution systems as well as conveyance systems, otherwise hydraulic unsteady conditions occur instantaneously in the entire canal system and the distribution loss also increases. Moreover, each operation of the distribution system should be carried out carefully not to delay but to shorten the resulting unsteady flow conditions.

VII. Concluding remarks

In this paper, the management of irrigation systems for rice double cropping culture in the tropical monsoon area was discussed based on the case studies carried out in the Muda Irrigation Scheme of Malaysia and the dry zone area of Sri Lanka.

In Chapter I, the background as well as the purpose of this investigation was described.

In Chapter II, the studies on the management of irrigation systems in Malaysia and Sri Lanka were reviewed based on political, socio-economic and historical aspects as well as on technical aspects.

In Chapter III, the natural environment, the current conditions of rice double cropping and management of irrigation systems in the case study areas were discussed. Here, a short-coming of the government-initiated large-scale irrigation schemes consisting of the lack of farmers' voluntary activities for the management of terminal facilities was pointed out.

In Chapter IV, a series of analyses on component factors of water management in the irrigation area was carried out and is summarized as follows:-

(1) The mechanism of water consumption and water requirement in terminal paddy fields was analyzed. The outline was described in paragraphs 2.6 and 3.7. The main aspects were as follows:-

① Coefficients of effectiveness for irrigation (Efi) and rainfall (Efr), which reflect the efficiencies of usage, were defined by Eq. (IV-6). A simple method to obtain the value of Efi and Efr was developed. By this method, the physical effect of the tertiary canal system could be evaluated quantitatively.

② The movement of water in paddy fields was simulated by a model based on the multiple regression equation (IV-3). By this model, the deep percolation (P) could be estimated.

③ The characteristics of runoff in a paddy field area could be expressed by the multiple regression models {Eqs. (IV-15), (IV-16)}.

④ The amount of percolation and seepage losses was so far underestimated in the majority of the irrigation projects. Especially, seepage loss was almost overlooked.

(2) Rainfall characteristics in the tropical monsoon area were analyzed based on the data obtained in the Muda area.

(3) The following subjects related to water management in terminal paddy fields were discussed.

① General trends of field water management [Appendix I].

② Percolation and seepage control methods [Appendix III].

③ Advantages of land consolidation for economical water management [Appendix IV].

④ Setting of suitable cropping and irrigation schedules [Appendix II].

In Chapter V, the components of reservoir management were analyzed and outlined as follows:-

(1) The characteristics of rainfall-runoff in the reservoir basin covered by tropical forests were analyzed.

① Runoff percentage varies from 20 to 37 with an average of 28. Rainfall loss ranges from 3.6 to 5.2mm/d.

② In a normal year, the actual annual runoff is only 640.7mm in depth, as against the designed value of 800mm in depth, or about 20% lower. This is one of the main

reasons why imbalance in water between supply and demand occurs in the Muda area.
③ From the time series analysis of the rainfall-runoff relationship carried out on a monthly, 10-day, 5-day and daily basis, the multiple regression equations (V-7), (V-8), (V-9) and (V-10) were derived.
④ The seasonal rainfall-runoff characteristics were analyzed and seasonal runoff estimation models were developed on a daily basis.
(2) The actual management of reservoir was investigated based on the case study in the Muda Scheme. The actual operational losses of the water released from the reservoir were estimated at about 19% for a normal year. Based on a series of analyses, a 'basic storage curve' was proposed (Fig. V-14).

In Chapter VI, the management of the conveyance and distribution system is discussed.
(1) Conveyance and distribution losses which consist of natural losses and operational losses were investigated based on on-site experiments and some trials. The results were summarized in paragraph 1.3.
(2) Based on on-site and numerical experiments, flow-arrival time was investigated in the long conveyance system. Although the results were summarized in paragraph 2.2, the concept of non-dimensional curve should be outlined as follows:-
① The applicability of equation (VI-8) to the initial ascending point of the non-dimensional curve is limited up to approximately 10km.
② For a canal system longer than 10km, the non-dimensional curve tends to pass the point (1.0, 0.582) which corresponds to the theoretical solution of uniform flow.
③ Estimation system of the flow-arrival conditions was proposed based on the non-dimensional curves obtained and the relationship between the water storage in the river canal and the released discharge from the reservoir.
(3) The problems and measures required to improve the management of the distribution system were studied and the main points were outlined in paragraph 3.4.

Since it can be anticipated that the competition in the usage of limited water resources with other industries will intensify in the future, studies on the management of irrigation systems will become increasingly important. Especially, the recycling of water will be the most effective measure to cope with water shortage. In case of the Muda Irrigation Scheme, it was concluded, based on a series of simulation analyses, that about 25% of drained water should be recycled so as to meet the deficit between supply and demand [Kitamura 1987].

However, it can be anticipated that some serious problems will arise in the practical recycling of water, namely water pollution and increase of percolation and seepage due to the lowering of the water level in the drainage zone, etc. Therefore, more research in this field is essential.

The author would be pleased if this paper could help the people engaged in irrigation planning and water management for rice double cropping in the tropical monsoon area.

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[APPENDIX I]
General trends of field water management

Based on the on-site study carried out in the case study areas, the following trends of field water management were recognized [Kitamura 1987] :-

(i) A farmer tends to take as much water into his field as possible and to drain the excess water off. This trend becomes increasingly conspicuous when the terminal irrigation and drainage system is improved and water can be easily controlled in each individual field.

(ii) In relation to (i), fields located in the upper stream of the terminal irrigation canal tend to retain a larger quantity of water due to the high hydraulic gradient between the canal and fields. Accordingly, fields located downstream are compelled to take in a smaller quantity of water.

(iii) Every farmer tends to delay purposely his field activities, such as transplanting and direct sowing, because he is afraid of rat damage that may occur during the ripening stage of the rice plant due to the absence of maturing crop in adjacent fields. This upsets the proposed cropping schedule in an irrigation scheme and results in the increase of water consumption.

(iv) In the government-initiated large-scale irrigation schemes, there are practically no farmers' voluntary activities for the management of terminal facilities. By organizing a functional water user association by the farmers themselves, this problems could be considerably alleviated.

[APPENDIX II]
Cropping schedule and irrigation schedule

1. Necessity and effects of the implementation of a complete fallow period and non-irrigation period on paddy cultivation

Cropping schedule and irrigation schedule are very important factors for the stabilization of rice double cropping in the tropical monsoon area and should be determined based on the climatic conditions. Especially, the implementation of a complete fallow period and non-irrigation period is indispensable.

In the Muda area, the decrease in rice yields in recent years is due to the extensive damage caused by rice tungro disease which is vectored mainly by the green leafhopper (GLH). M. Nozaki is advocating the necessity of introducing a one-month complete fallow period simultaneously practiced over the whole area as the most effective method of control [Nozaki et al. 1984]. As a result, rice and other host plants of GLH could be eradicated over the whole area and the life cycle of GLH and other insect pests interrupted.

The non-irrigation period should be implemented concurrently with the complete fallow period. In this paper, the terms 'complete fallow period' and 'non-irrigation period' are defined as follows:-

(i) Complete fallow period is defined as the period from the completion of the wet (main) season harvest to the seeding time of the next dry (off) season crop.

(ii) Non-irrigation period is defined as the period from the discontinuation of the water supply for the wet season crop to the beginning of the presaturation period for the dry season crop.

When the ripening stage is over, water supply is not necessary for the rice plant and should be discontinued. The interval between the end of the ripening stage and harvesting time is about 15 days. The interval from the beginning of the presaturation to the seeding time for the dry season crop also lasts about 15 days. Therefore, the non-irrigation period precedes the complete fallow period by 15 days.

By implementing a complete fallow period and non-irrigation period, the following effects, in addition to the control of GLH and other insect pests, can be expected:-

(i) Effect on water saving.
(ii) Increase in soil bearing capacity [Anyoji 1978].
(iii) Increase in yield by soil-drying effect [Miyake 1980, Nozaki 1983].
(iv) Facilitation of repair and restoration of irrigation facilities.

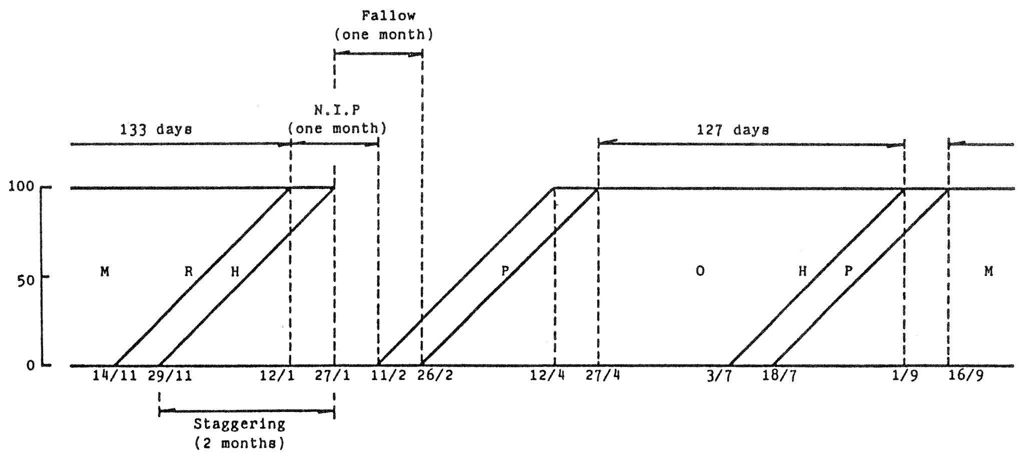
2. Suitable cropping schedule and irrigation schedule in the Muda area

The non-irrigation period should be inserted during the driest period so as to maximize the effects described previously. In order to select the driest period in the Muda area, fourteen (14) years of rainfall data which have been collected since 1971 at 56 rainfall observation stations were used.

In case of one-month complete fallow, the one-month non-irrigation period is to be set half a month prior to the one-month fallow. Based on the analysis, the period from January 12th to February 10th is considered to include the driest continuous 30 days which should correspond to the non-irrigation period in the Muda area. Therefore, the one-month fallow period simultaneously practiced over the whole Muda area should be inserted between January 27th and February 25th.

For the setting of cropping systems, it is necessary to prevent the heading and flowering stages of rice plant from coinciding with the period between the middle of January and the beginning of May during which high temperatures above 34℃ which are responsible for spikelet sterility are frequently observed [Nozaki 1984]. It is also important to prevent the harvesting stage from coinciding with the heavy rainy season starting from the beginning of September.

Therefore, the most suitable cropping schedule is summarized as shown in Fig. A II-1. In addition, it is desirable to use varieties and adopt methods of crop establishment which enable to harvest the crop within 127 days for the dry season and 133 days for the wet season, respectively. [Kitamura 1985, 1986]



P : Presaturation period
O : Dry (Off) season crop
M : Wet (Main) season crop

N.I.P : Non-irrigation period
R : Ripening Period
H : Harvesting period

Fig. A II—1 Suitable cropping system with one month of fallow and two months for crop staggering, Muda Scheme, Malaysia.

[APPENDIX III]
Percolation and seepage control methods

The amount of percolation and seepage is comparatively large in terminal paddy lots in the dry zone area of Sri Lanka as indicated in paragraph 1.2.3 in Chapter IV. However, there are many instances where the percolation and seepage losses are estimated at only 2~4mm/d in the dry zone area. Therefore, from the standpoint of effective water use, it is necessary to promote studies related to methods for controlling percolation and seepage in the tropical monsoon area.

In this study, the following methods were evaluated with respect to their effectiveness on a small scale in the detailed study lot in the Rajangana Scheme [Kitamura 1984].

a. Subsoil compaction method
b. Subsoil puddling method
c. Crushing and compaction method
d. Bentonite dressing method (stratifying type)
e. Bentonite dressing method (mixing type)

It was observed that the application of subsoil compaction, crushing and compaction, and bentonite dressing (both stratifying and mixing) methods reduced percolation and seepage to below 10mm/d (Table A III-1).

Table AIII—1 Effect of methods for the control of percolation and seepage, Rajangana Scheme, Sri Lanka.

Method		1978/79 Maha Percolation[1) (mm/day)	1979 Yala Percolation[1) (mm/day)	1979 Yala Percolation[2) (mm/day)
Subsoil compaction	Test plot	4.5	4.7	2.4
	Control	23.5	45.6	15.3
Subsoil puddling	Test plot	22.8	12.3	14.0
	Control	25.9	28.9	14.5
Crushing & compaction	Test plot	7.6	7.7	12.0
	Control	26.2	31.5	25.5
Bentonite dressing (mixing)	Test plot	—	8.6	3.5
	Control	—	27.9	13.7
Bentonite dressing (stratifying)	Test plot	—	12.1	6.2
	Control	—	29.3	18.5

Notes: 1) ------Percolation was measured by using 'Quick percolation measuring apparatus'.
2) ------Percolation was measured by using 'N-type water requirement measuring apparatus'.

[APPENDIX IV]
Advantages of land consolidation for economical water management

Here, the dry zone area of Sri Lanka was selected as the study area [Kitamura 1984].

A 'lot' is the most terminal irrigation unit as well as the unit of paddy land tenure where plot-to-plot irrigation method is adopted. An ordinary lot is irregularly divided into a large number of small plots by dykes of poor quality in the dry zone. This condition makes proper water control difficult in each plot and increases surface runoff through the outlet of the lot. In the case of the Dewa huwa Scheme, it took more than two hours for two persons working actively to interrupt the water movement of 110 plots in a 2.0ha lot. Namely, it is physically impossible to interrupt the water movement and to substitute plot-to-plot irrigation for ponding irrigation. Even though the intermittent irrigation method is adopted under the present conditions of the lot, it is hardly effective. In order to promote economical water management in a terminal lot, land consolidation should be given a high priority.

In this study, the effectiveness of land consolidation for economical water management was investigated by comparing a consolidated lot with an adjacent non-consolidated lot in the Dewa huwa Scheme. According to the investigation, the advantages of land consolidation for economical water management were as follows:-

(i) Land consolidation enables to achieve proper water management by rearranging and converting 'a large number of small and irregularly distributed plots' into 'a small number of large and regularly arranged plots' in a lot. Accordingly, consolidation work in paddy fields further increases the benefit of the application of the intermittent irrigation method (Table A IV-1).

(ii) In the process of implementation of land consolidation, paddy soil is compacted and puddled by heavy machinery resulting in the reduction of percolation (including seepage) and dyke-leakage. The observed percolation was only 2mm/d in the consolidated lot in contrast with 9mm/d in the adjacent non-consolidated lot (Fig. A IV—1).

In addition to the above advantages for economical water management, land consolidation leads to the improvement of land and labour productivity as well as land conservation, etc. Therefore, land consolidation is very important if the dry zone area of Sri Lanka is to become a major food production center.

Table AIV—1 Difference between two experimental lots in the Dewa huwa Scheme, Sri Lanka.

Items	Consolidated lot (2—5)	Non-consolidated lot (2—6)
1. Number of plots	small number (21 plots)	large number (110 plots)
2. Average area per plot	large (9.5 ares)	small (1.8 ares)
3. Shape and distribution of plots	well distributed	irregularly distributed
4. Structure of dyke	strong	weak

Fig. AIV—1 **Comparison of water storage between consolidated lot (left) and non-consolidated lot (right) two days after water intake, Dewa huwa Scheme, Sri Lanka.**