Water Saving Practices in Rice Paddy Cultivation
(State-of-art report on irrigation systems in Japan)

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1. Introduction

Paddy cultivation uses large quantities of water usually under ponded condition. Paddy fields with artificially controlled hydrological condition, namely irrigation, covers about half of the whole paddy field area in the world, and it produces three-fourths of the total world rice production.

Paddy rice culture is sustainable at high productivity because of special cultivation systems, especially in Japan. In wet paddies, the surface soil is ponded, and seepage through the root zone removes salts and other toxic constituents. This is the reason why rice culture could be carried out continuously for more than 2,000 years in the same fields. Furthermore, rice yields have been increasing with advances in the science and technology of rice cultivation.

In Japan, rice is held as the national crop, and excellent varieties of rice, standardized fertilizers and pesticide applications, and improved water management have all assured a high and stable productivity of rice. In addition, labor savings in paddy rice cultivation is an important characteristic. By ponding water, weed control is minimized, whereas this feature of cultivation is one of the most laborious tasks in upland fields. Because of land leveling, agricultural machinery can easily be introduced and efficiently worked. Another labor-saving option is the machine planting of rice seedlings (Maruyama and Tanji,1997).

Water saving practices in rice paddy cultivation are conducted in field level and project level. The field level practices are the soil puddling to decrease percolation, the intermittent irrigation, the accurate water consumption measurement, the water level controller installation, cyclic use of irrigation water, and so on. For the project level practices are introduction of the pipeline water delivering system, optimal system control by the computer and the utilization of the information on weather and crop growing conditions.

2. Paddy Field Conditions for Rice Cultivation

In paddy fields, there are necessary conditions for rice growing besides water, like allowable temperature, adequate daylight hours, abundant sunshine and suitable soil. Compared with these conditions, water is controllable except in the flood-prone areas mentioned above. Average water requirement of rice for growing under stable water supply is 220 to 280g per g of matter, which is almost equivalent to other plants with the same photosynthesis type C3 as rice. However, rice has some sensibility to water stress and some tolerance to water excess. Therefore, water condition of rice growing field, i.e. paddy field, is to be controlled to keep adequate water supply under submergence condition, usually eliminating the risk of water deficit.

Submergence of paddy fields by irrigation helps in the followings (Tanaka, 1978).

a) Stabilization of water supply to rice plants,

b) Increased supplies of Nitrogen and Phosphorus and control of organic matter dynamics,

c) Supply of inorganic mineral salts contained in irrigation water,

d) Weed control,

e) Prevention of damages by blight and harmful animals, insects, and other living things, and

f) Maintaining temperature.

3. Rice Growing Calendar and Water Management

Fig. 1 shows the growth stages of transplanted rice and associated management practices in Japan. Rice is sown in nursery beds, germinates in 5-7 days, and divides into several stalks in 25-30 days. At that time, the seedlings are transplanted into wet paddies which had been already prepared. About 30 days after transplanting, the stalks begin tillering reaching a maximum number of tillers. 70-80 days after transplanting, young ears form. This is called heading. About 40-50 days after heading, rice can then be harvested. Thus, the growth of rice plants can be divided into ten growth stages as shown in Fig.1.

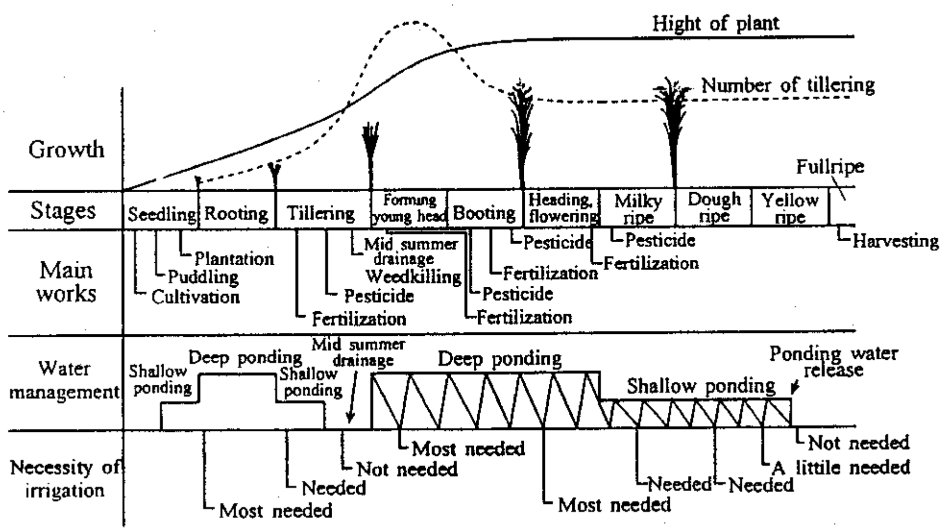


Fig. 1 Rice growth, agricultural works and water management (Maruyama and Tanji,1997).

A number of water management practices are carried out in accordance with these agronomic practices and growth stages of rice. In order to establish the seedling transplants and to eliminate excess water seepage, soil puddling has to be done before transplanting. Because of potentially large loses from percolation, this is a very important practice for saving water needed in paddy rice culture. After the puddling, a relatively shallow water level is maintained in the paddy. At that time, suitable ponding depth of water 2-3 cm because of the small height of the young nursery transplants. After transplanting, the ponding depth is gradually increased as the height of rice increases. During the tillering period, the ponding depth is kept shallow again to increase the soil temperature and promote the tillering. In midsummer, paddy field is drained so that the soil surface is kept at non-ponding conditions for 7-10 days, and by this form of water management, sufficient oxygen is supplied to the root zone of rice, and toxic substances such as sulfides and organic acids are drained.

After the mid summer drainage, intermittent irrigation is carried out in almost all areas of Japan. Following this stage, ponding of water usually cannot be kept as shallow as before since much water is required for rice in the ripening stage. Thus, the ponding depth is increased about 10-14 cm. After this stage, intermittent irrigation is repeated, that is, periodically maintaining ponding and non-ponding condition. This laborious water management can save water comparing with the constant ponded fields. In the yellow ripening stages, ponding water must be drained for harvesting, known as harvesting drainage. Usually, the period from transplanting up until this drainage is about 100-110 days.

The standardized calendar of water management and cultural practices for rice in Japan are those mentioned above. However, there are special cases depending on regional characteristics corresponding to differing varieties of rice, soil moisture conditions, availability of irrigation water supply, climate of the region, etc., that may differ from the normal or standard practices.

Drainage is required in midsummer, before harvesting and during the non-irrigation period. If the drainage is insufficient in this period, non-ripening tillers increase, and the efficiency of harvesting may decrease. For this reason, drainage of ponded water, which means surface drainage, became a key technology (Maruyama and Tanji,1997).

4. Water Balance in Paddy Fields

4.1 Water Balance Equation in Paddy Fields

The water balance equation of a paddy field can be expressed as follows,

$$R + Qi = ET + P + Qo + \Delta S \qquad (1)$$

where R is precipitation, Qi is the irrigation water ET is the evapotranspiration , P is the percolation, Qo is ⊿S the change in storage. When the budget include the rice and the soil rhizosphere, the storage S includes both ponded water and water content in the soil profile.

ET consists of evaporation (E) from the water or ground surface, and transpiration (T) from rice plants. Percolation (P) is a balance of seepage away from the budget domain and groundwater intrusion from outside of the domain. Usually, P is positive since some water is ponded on the field surface. Surface runoff (Qo) includes runoff of excess rainfall which cannot be stored in the plot and spillage or drainage of water which has been applied or stored.

In hydrological practice, the elements of water budget, i.e., the terms of Eq. (1), are usually expressed in units of water depth per day. Fig. 2 is a schematic representation of the elements in the water balance equation of a plot, which is adjacent to both irrigation canal and drainage canal.

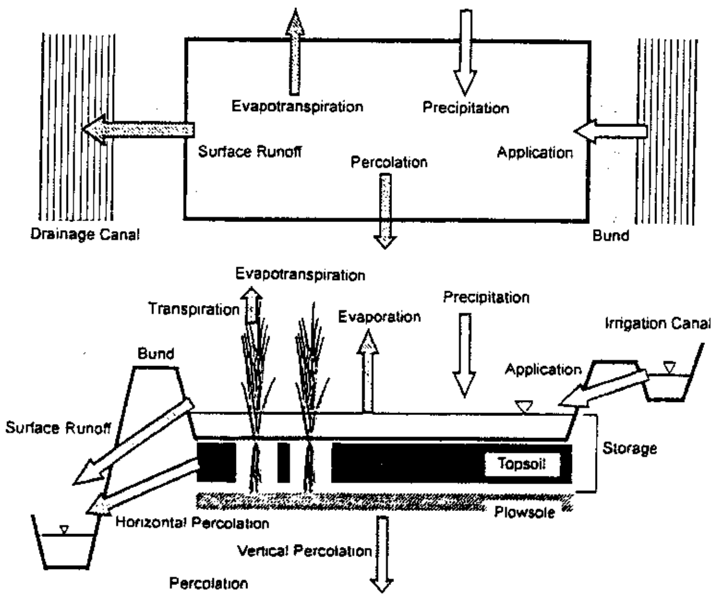


Fig.2 Schematic representation of the water budget in a paddy field plot (after Watanabe, 1999).

4.2 Factors Involved in Water Balance

Water balance is greatly influenced by the terms on the righ-hand side of Eq. (1), because farmers usually irrigate in accord with the water consumption and requirement of their plots. Although the consumptive elements on the right-hand side and the water supply on the left-hand side are inseparably related, water application normally follows the fluctuation of water consumption.

Strictly, only evapotranspiration (ET) is consumption in a plot. It is influenced by meteorological conditions and stage of growth. Percolation (P) consists of horizontal (bund) and vertical (deep) components. Horizontal percolation flows through the topsoil over the plowsole and seeps into the field drainage canal or adjacent lower field plots. Vertical percolation passes through the plowsole and finally joins the groundwater, which may come to the surface far from the plot site. The percolation rate is determined by the hydraulic conditions of the plot, such as the hydraulic gradient between the ponded water and the water table in the drainage canal or groundwater, and the permeability of the soil and bunds.

Evapotranspiration and percolation are the major consumptive elements in a paddy field plot with vertical percolation accounting for a large part of fluctuation in total consumption. Factors influencing evapotranspiration and percolation are shown in Fig. 3 (Nakagawa,1967) . While it might be thought that the these are affected only by natural conditions, Fig.3 shows clearly that cultivation and water management practices also influence them. In addition, much percolation results in increase of water requirement and should be avoided in plots with poor water resources.

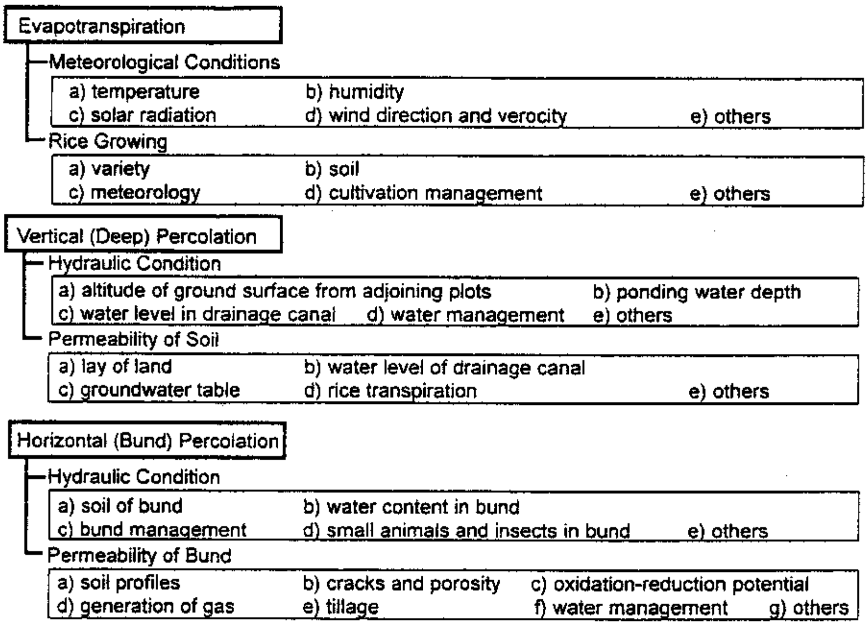


Fig. 3 Factors influencing evapotranspiration and percolation (after Nakagawa, 1967)

4.3 Method for Measuring Evapotranspiration and Percolation

Since evapotranspiration and percolation are the major consumptive components of water budget in a paddy field plot, it is important to measure or estimate these values for calculating the actual water requirement in the plot as well as establishing a basis for irrigation planning.

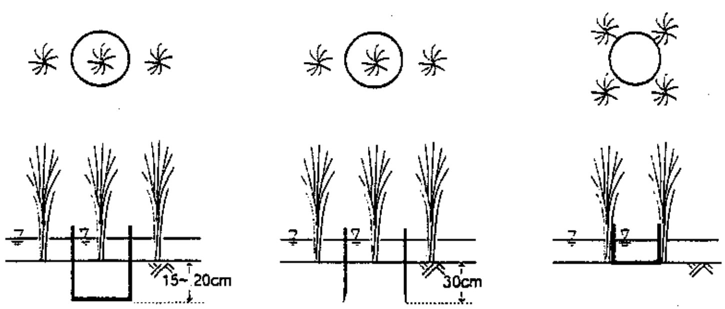
Actual evapotranspiration can be measured in a plot using a small lysimeter with the bottom set in the topsoil, in which some rice plants are growing, as shown in

Fig.4(a). Since water in the cylinder is consumed only by evapotranspiration, its rate can be measured as the decrease of the water depth in it. If evaporation rate is to be separated from evapotranspiration rate, it can be measured using a similar pipe without rice plants as Fig.4 (c). While Fig.4 shows examples of the measuring cylinder with only one plant hill, the cylinder which contains more rice plants is better for more accurate measurements, however it may cause some troubles in the placement of the more heavier apparatus.

Evapotranspiration rate can be estimated by climatological methods like the energy balance method or the mass-transfer method, or using estimated by free water evaporation rate which also can be estimated by the climatological methods (Bras, 1990).

Actual percolation rate can be measured in a plot with the cylinder without a bottom as shown in Fig.4 (b) . The rate of decrease of water table inside the cylinder gives the rate of water consumption by percolation and evapotranspiration. Therefore, using the evapotranspiration rate measured with the other cylinder (Fig.4 (a)) , percolation rate can be calculated. In this system, water table in the cylinder should be held at the same level as the outside water table. In Japan, simple apparatus considering this condition was developed, which has a rectangular cross section, and named the N-type percolation meter(Nakagawa, 1967). A device similar to Fig. 4 (b), which is placed in the plot and against the bund with an open side, will give a measure of horizontal seepage through the bund soil as well as deep percolation and evapotranspiration. Bund horizontal percolation is estimated by difference between this bund seepage meter and Fig.4 (b).

Average evapotranspiration and percolation rate in a whole plot is calculated by the observations of the other components in water budget of the plot. Usually, when the conditions of no rainfall, no water application and no surface drainage is selected, then the evapotranspiration and percolation rate can be observed as the fall of the water surface in the plot (after Watanabe, 1999).



(a) Evapotranspiration (b) Evapotranspiration and percolation (c)Evaporation

Fig.4 Example of measuring apparatus for evapotranspiration and percolation rate

5. Effective Rainfall on Paddy Plot

When a field plot has rainfall during the irrigation season, the rainfall can be used as the same as applied water. In that case, rainfall is available and effective to rice production, water requirement can be reduced by rainfall effectively used in a plot, leading to net water requirement.

The amount of rainfall stored and used in a plot depends on the amount and intensity of rainfall itself and field conditions of the plot, including height of bunds and sill of outlet, depth of standing water, water consumption during the rainfall event, and water management practices which a farmer introduces in and after the storm. Farmers try to store and use rainfall on their plots for rice production as much as possible, when water supply to the plots is insufficient.

6. Supplier-led and User-led Water Control Systems

In the irrigation system using open channels, irrigation water is taken at the head and is distributed from offtake. The water distribution manager, who is chosen among the farmers and who has the responsibility to judge the distribution amount, observes the flow condition in canals and controls the discharge using the distribution facilities.

Modern irrigation systems using open channels are managed in the same way as the traditional systems. In the water control system for the mainlines, the water level is kept constant at the checks (Fig.5 (1)). The supplier (water distribution manager) determines the intake discharge at the head and watches the distribution at the offtakes and the checks. It is not necessary to change the intake discharge even if a downstream offtakes can not take enough water due to excessive withdrawal from upstream offtake. The supplier calls on farmers to arrange the allocation of the water.

Thus, the system is a supplier-led water control system. From a hydraulics point of view, the supplier, irrespective of the water demand, can control the intake discharge at the head in the system. This supplier-led system of irrigation control is the traditional one, and farmers are accustomed to it. Accordingly, modern open channel irrigation systems have been managed without difficulty.

However, the introduction of the pipeline system for irrigation produced a radical change in the supplier-led water control system (Fig.5 (2)). A benefit of the pipeline system is that farmers in the system can take as much water as they want, if they open or close the valve at the end of the system, water will come out or stop. In the pipeline system, users control the water, and thus it is a user-led water control system.

The user-led system cannot be controlled at the head of the system. Usually, the head of the pipeline is located comparatively high. If one sets and controls the valve at the head, cavitation or air entrainment in the pipe can easily occur. Air will also enter the pipe if the water supply is insufficient. Consequently, the user-led water control system is possible only when there is an adequate water supply at the head.

In the user-led water control system, the supplier does not need to control the facilities under usual conditions, but must ensure an adequate supply of water at the head of the pipeline, even in case of overuse by the farmers. The introduction of a pipeline system requires the water control system to be changed from the traditional supplier-led one to the user-led one.

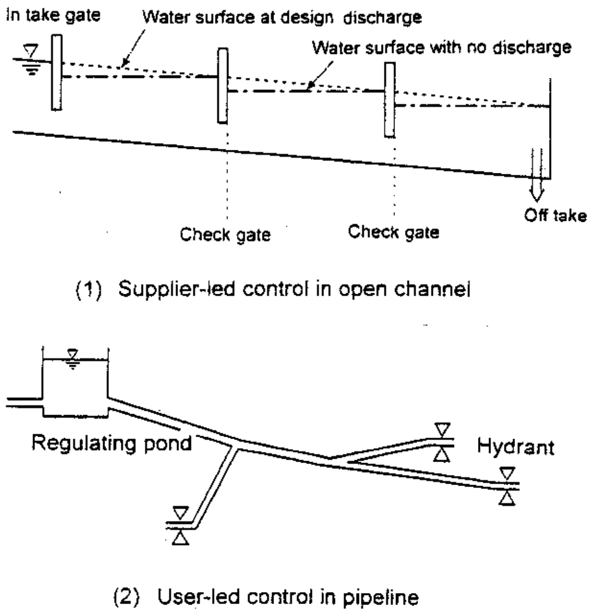


Fig.5 Water control systems in pipeline and open channel

Closed type pipelines, shown in Fig. 5 (2), are used in the user-led water control system. There is nothing for the water supplier to control and operate directly in this water management system. The supplier only checks the flow condition in the irrigation system whether irrigation water is distributed properly or not. If the supplier finds overuse of water in a certain area, he can only call for the farmers to adjust the water use by controlling hydrants at the end of the system. Therefore, it is not necessary to introduce special automatic control facilities for the pipeline systems.

Table 1 shows the characteristics of the supplier-led and user-led water control systems. There are some disadvantages of user-led water control systems. Resources of irrigation water are mostly rivers, and there are many water users in a river. It is very difficult to take sufficient water from a river. The users are required to take water constantly in accordance with the schedule set in advance. So the supplier of a irrigation system have to withdraw water constantly from a river. In case of withdrawal of water more than the scheduled or during drought, reallocation of water among the users is necessary. Thus, supplier must control the water supply to the irrigation system not only in case of open channel but also incase of pipeline which leads the water control system to the user-led one.

Table 1 Characteristics of water control systems (after Usuki, 1999)

Systems	Advantage	Disadvantage
User - led	1. farmers water use at will	1. secure sufficient water supply
	2. relief of data collection and facilities operation work	2. altered flow condition
	3. lessening useless water	3. necessity of special measure against water shortage
Supplier - led	1. deliberated water supply and distribution	1. necessity of data collection and facility control
	2. constant flow condition	2. increase of ineffective water

7. Operation and Control of Main Channel Systems for Saving Water

The irrigation water requirement varies mainly with the rainfall. The frequency of changing the water supply to suit the requirement used to be weekly or seasonally, but recently daily changes are required for effective water use and quick response to the demand f0r water.

After introducing a pipeline, hourly changes in water requirement can not be ignored. As the pipeline system should be operated using the user-led water control, the supplier must supply water following the hourly changes at the head of the pipeline. However, it is very difficult to monitor and operate the facilities while flow condition in the irrigation system is fluctuating.

If there is a stock of water in the system, stored water can be allocated to balance supply and demand. A steady water supply in the main irrigation system can be realized with a regulating pond. The pond is usually located at the end of the main irrigation system as shown in Fig.7 A regulating pond obviates the need for frequent operation and water control, and also gives important information and time for the supplier to consider. The supplier can have enough time to observe the flow condition of the irrigation system and to determine how to control the facilities properly. Information on any imbalance of water supply is indicated by the water level and its change. Especially during droughts, this information is a key index by which the supplier can use to supply water to a specific area where the water shortage is serious.

There is another type of regulating pond necessary for reasonable water management. At the head of the pipeline, a sufficient water supply is essential. There are many irrigation projects which combine with open channels and pipelines. The response to the change of now in the open channel is slow, and it takes time for the discharge at the downstream point to change from one to another. It is called the flow arrival time (Iwasaki, 1981). If the supplier could know the change of demand in the pipeline and change the intake discharge at the head of the open channel, enough water could not be supplied to the pipeline in time because of the flow arrival time. Therefore, regulating pond at the connecting point of the two systems is required

(Fig.6). A regulating pond provides stored water to the pipeline during the flow arrival time in case the demand increases, and stores water when the demand falls. Water stocks such as regulation ponds in irrigation systems should be taken into account for smooth and efficient water management.

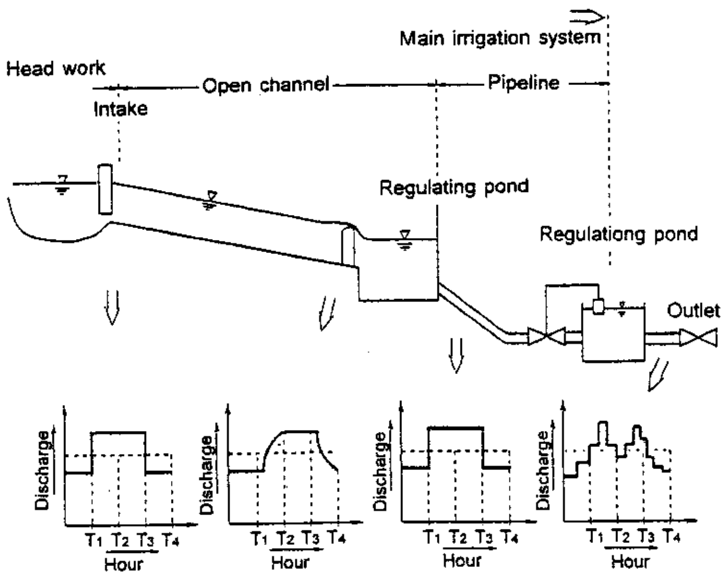


Fig.6 Time-Discharge relation in irrigation system(Yoshino, 1990)

Irrigation facilities such as dams, head works, pumping stations and checks offtake gates, have traditionally been individually monitored, operated and controlled at each site. Such individual management systems are now being replaced by a centralized control and management system in which all the main facilities are monitored and controlled from a central station.

The reasons for introducing central water management systems are as follows :

(1) Effective water use with the least losses,

(2) Proper water supply and distribution to meet water requirement,

(3) Harmonized water management of supply with demand in the irrigation systems, and

(4) Reduction of management cost.

Main irrigation facilities are controlled from a central station in a centralized water management system. Operators at the station can control the irrigation facilities such as main canal regulators with remote control system without local operators at all the local sites. Observation data are required for proper facilities control and a telemetering system is installed to collect necessary data of water level, discharge, etc. Thus a telemetering and telecontrol system is necessary for the centralized water management system.

8. Operation and Control of Farm Level Water Management for Saving Water

8.1 Closed Type Pipeline System

The supplier-led water control system is preferable for the main irrigation system. The use-led water control system is preferred at the secondary and field irrigation system because of the convenience of water use for the farmers. The most important matter for operation and control of the farm level water management is how to realize user-led water control system and how to harmonize the field irrigation system with the main irrigation systems. For this purpose, regulating ponds and discharge control facilities such as valves should be installed at the connecting points of the main irrigation system and field irrigation systems.

In recent years, automatic hydrants to control water level have been introduced to the paddy fields (Fig.7). The hydrants is automatically opened and closed according to the water depth of a paddy plot. The sensor for measuring depth is mechanical one using float, thus electricity is not necessary for the automatic control of the hydrants. Introduction of pipeline system and such equipment as the automatic hydrant to the field irrigation system accelerate the concentration of water use. The concentration of water use at a particular time causes fluctuation in water demand and unequal water distribution. The requirement of water use often goes beyond the capacity of the irrigation system, and the adjustment of water use among farmers should be carried out by the supplier.

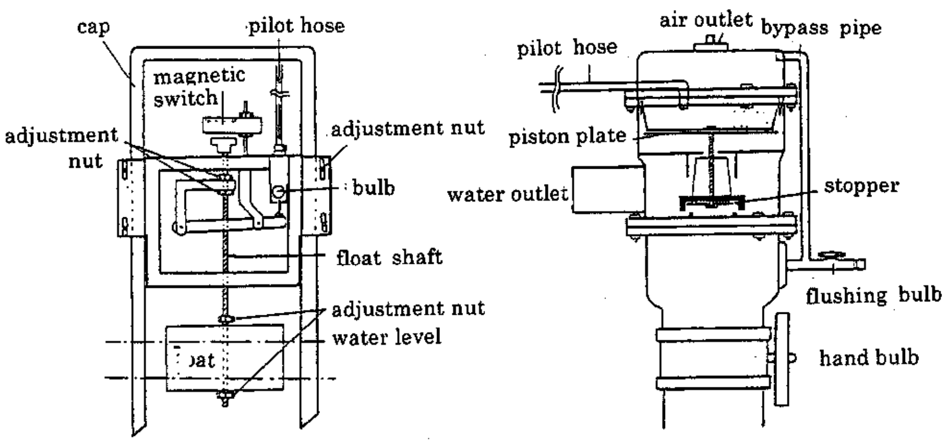


Fig.7 Automatic hydrant for water depth control

It is not easy to detect a overused hydrant from a large number of hydrants in a pipeline system, and the problem becomes so complicated as the operation of one hydrant may produce an effect both on the flow condition of the pipeline system and the discharge of other hydrants in the system. If the size of the irrigation network is comparatively small, it is possible for the farmers to adjust the hydrants for keeping distribution balance.

Partition into small blocks of irrigation network is recommended for this purpose (MAFF, 1998). Fig.8 shows a pattern of partition of irrigation network. From the result of hydraulic analysis, the size of the irrigation block less than 20 ha is appropriate to the partition. It is also desirable to install discharge control valves at the entrance of each blocks. These valves work to control the flow keeping good balance among the blocks.

Automated operation and control at farm level using personal computer has been attempted (Tanji and Usuki, 1995). For further development of the automated water management at the farm level, irrigation network design and discharge control such as partition of the network are important.

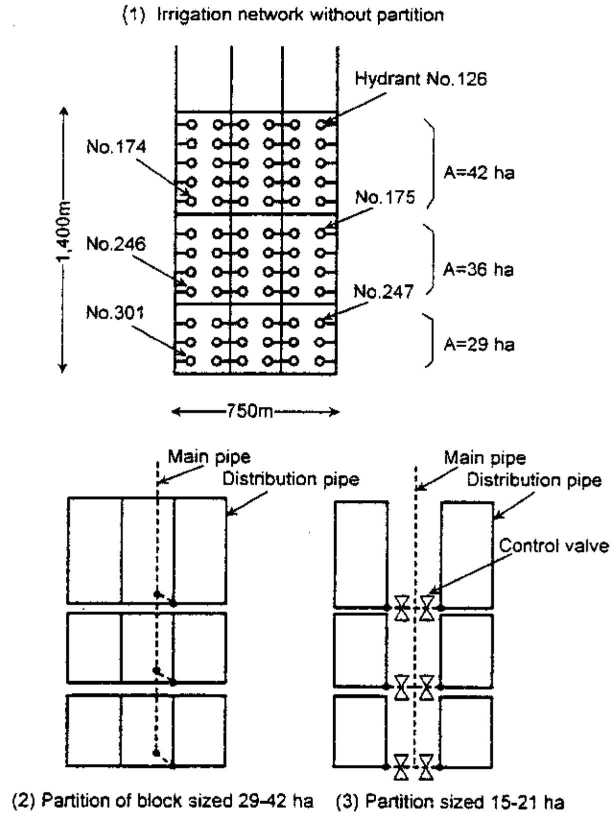


Fig.8 Partition pattern of irrigation network blocks

8.2 Cyclic Water Use System

Fig. 9 shows the circulation system to use drained water repeatedly. Ponding depth of paddy field and water circulation pump are regulated by the computer. The consumptive water is supplied from irrigation pipe automatically with float type hydrant. The water in the drainage channel is also used for irrigation water supplement. The irrigation efficiency of this system is extremely high as water is consumed only by evapotranspiration and deep percolation. Sometimes this system is used for subsurface irrigation in direct seeding culture to control soil moisture suitable for rice.

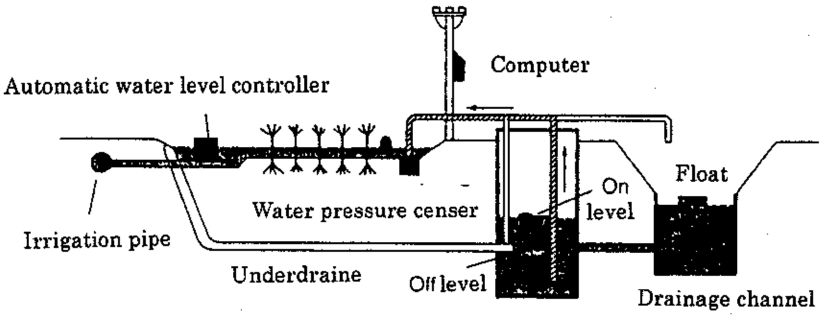


Fig. 9 Cyclic water use system

9. Computer Model for Water Management Technology

9.1 Adoption of Water Management Technology

At present, computer technology has been developed well and there are various approaches of water management technology using personal computer. One direction of the new technology is to strengthen the centralized control and management system (Iijima et.al.,1995). Development of software to support excellent water control utilizing database system and mathematical model with visual aid is an example. Fig.10 shows such kind of water management information system. This information system is useful for not only water control but also facilities maintenance, evaluation of water management and other services for water management.

Another concept of new technology for water management can be expressed as a kind of cooperation of various systems with advanced network technology (Tanji and Usuki, 1995) . Present water management system is the system only for the main irrigation systems, but the importance of farm level water management is recognized. Therefore, total water management system which covers all the irrigation systems from the main channels to the field channels should be developed. Harmony of the central water management system with the farm level water management systems should be considered for the development of the total water management system.

Water management of irrigation systems usually has been under taken by Land Improvement Districts (association of farmers in a certain area in Japan). However, in general, the management engineer of the district is not accustomed to operate a central control system, which is not easy to operate without necessary knowledge and experience, and may give up using the systems in some situations.

A simulator has been developed by National Research Institute of Agricultural Engineering, Japan, to train the use of the central control system (Nakahori and Horikawa,1993). The simulator consists of the console, display and computer system shown in Fig. 11. A mathematical model of an irrigation system is used to calculate the canal flow condition in the computer. The computer system uses the mathematical model to calculate the flow condition at certain times, and the display system shows the calculated flow condition continuously the same as actual operation. One can thus learn how to operate the control system, and any desirable conditions can be simulated. Modern control systems such as computer-based water management systems are not easy for operating staff without any experiences in use of such software. Therefore, the simulator is an important tool for dissemination of computer-based water management technology.

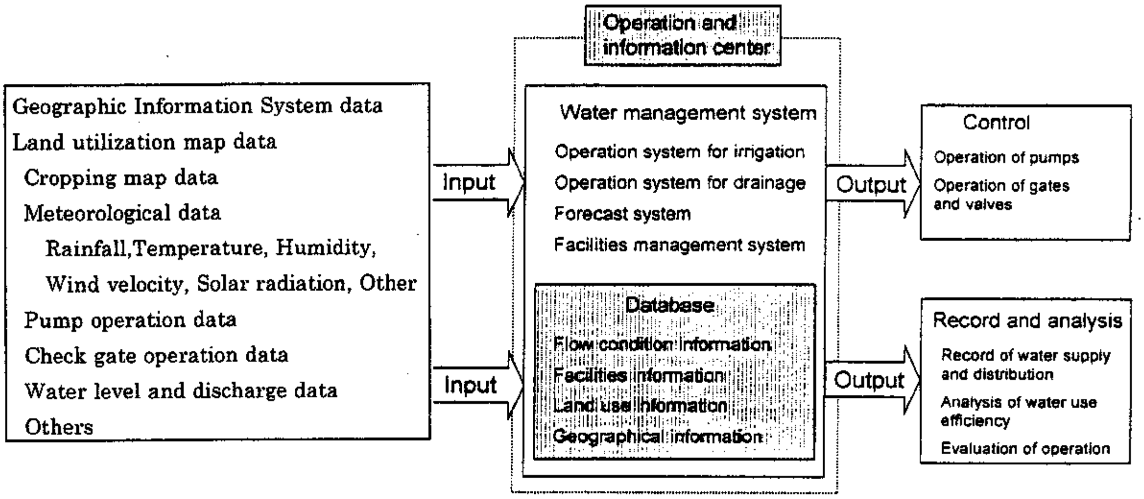


Fig.10 Example of water management information system

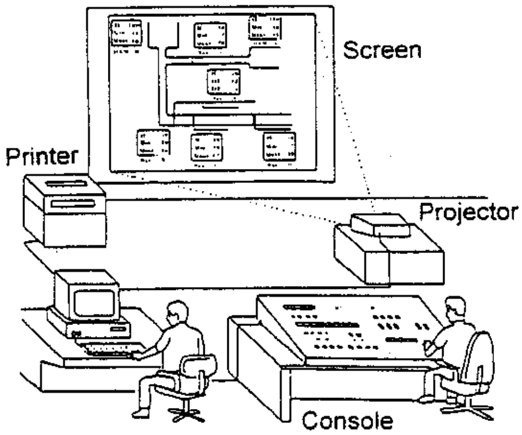


Fig. 11 Outline of simulator

9.2 Computer Support for Water Management

Analyses using mathematical simulation models and computer software are becoming popular. Hydraulic model experiments have been conducted to study the unsteady flow condition in irrigation systems. Mathematical models for the planning and design of irrigation facilities are useful in irrigation management. Shiraishi and Nakamichi (1993) have compiled mathematical simulation models and computer programs for irrigation and drainage.

For instance flow arrival time has been estimated from the unsteady flow analysis (Fig. 12) . Changes in the flow condition at downstream points along a canal can be described by the analysis. Various water-control systems have been examined and necessary facilities such as regulating ponds were introduced to a irrigation system. Dischar9eatadownstreampoint

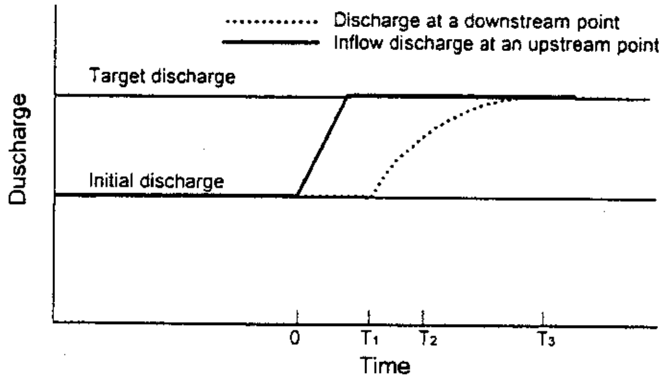


Fig.12 Discharge condition in a canal

It is also possible to employ such computer-based mathematical analysis for water management, but the analysis of unsteady flow is some what complicated and takes time and expertise. This is the reason why such analysis is not widely used for daily water management.

A computer program called "Nuflow" has been developed for daily water management in open channel irrigation systems (Yoshino et.al.,1997) . This program uses mathematical analysis of non-uniform steady flow and can calculate the flow arrival time in an open channel very quickly and display the information visually. If an initial and target discharge is given, water surface in a canal can be estimated by non-uniform steady flow analysis. The flow arrival time of target discharge at any points .

10. Water Management Information System

Water management is like a loop, from observation and data collection to data processing, analysis, operation planning and operation of facilities, then back to observation and data collection. We can define the water management information system as a system which gives information to help these tasks using computer－based technology.

There are many kinds of information used for water management as shown in Fig.10. We also can get information such as facilities maintenance, management costs, etc., from databases through information processing. To establish an effective water management information systems, accuracy and reliability of the data are critical. Indexes for water management information are also important and should be selected carefully.

Because of the fluctuations of water demand and frequent changes of water supply, the volume of water supply and consumption in a day or in a week are the main index is for daily water management. Water management information systems are still being established, and the storage, supply and consumption volume of water in an irrigation system should be considered as key information indexes for effective water management.

11. Research needs

In irrigation systems management, there is a need to adopt computer-based water management systems. The adoption of such systems needs technical skill and experience.

Flow conditions in irrigation canals can be well described by unsteady flow equations. Model based on unsteady flow condition need to be adopted for the control and operation of large irrigation systems.

Water management information systems considering the storage, supply and consumption will help in the efficient use of water in irrigation systems. This is a need to develop used friendly suited for each system for practical daily water management.

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