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Enhancement of Buffer Function in Irrigation Canal Systems

2. A method for deciding buffer capacity

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Abstract

In the course of modernization of agricultural techniques, especially consolidation of terminal irrigation facilities developed in Japan during the last decades, water requirement for irrigation has considerably increased, being accompanied by its magnified fluctuation. To rationalize water use in irrigation, attempts have been made to improve facilities. However, the present canal systems in Japan do not justify the increased fluctuation in water requirement. To resolve this problem, a buffer function has to be adequately incorporated to the canal systems so that water resources could be utilized effectively. With a large buffer function, the water management could be more easily operated. However, in view of limited size caused by socio-economic conditions in the country, an optimum size of buffer function has to be designed. The basic concept of buffer function and the necessity of its enhancement are described in the earlier part of the present paper. A method for deciding an adequate buffer capacity, taking into consideration changes of stored water in canals and delay time in operation, is proposed in the present part. A proposed formula is: $N_v = \Delta V + \int_{T1}^{T2} (Q_0(t) - Q_{in}(t))dt$, where ΔV is changes of stored volume and the second term of right member means volume in delay time in operation. Availability of the proposed method is confirmed for various canals using an unsteady flow simulation model. Effects of various countermeasures for the enhancement of buffer function including cheek-gates are also examined.

Discipline: Irrigation, drainage and reclamation

Additional key words: cheek-gate, equations for estimating buffer volume, unsteady flow simulation

Calculation method for buffer volume in irrigation canal systems

1) Equations for calculating buffer volume

The authors have derived several equations, as presented below, which would calculate necessary buffer volume for irrigation canal systems, using an unsteady flow simulation model[3].

In the first place, assuming that the irrigation system is composed of an open canal and a buffer pond which functions as a water storage facility, the following equation (1) is derived irrespective of the situation whether the pond and the canal are hydraulically separated or not (Figs. 1 & 2):

$$d(R + C)/dt = Q_{in}(t) - Q_o(t), \quad \text{............... (1)}$$

where R : storage volume of buffer pond (m^3);
C : storage volume of open canal (m^3);
t : time (seconds);

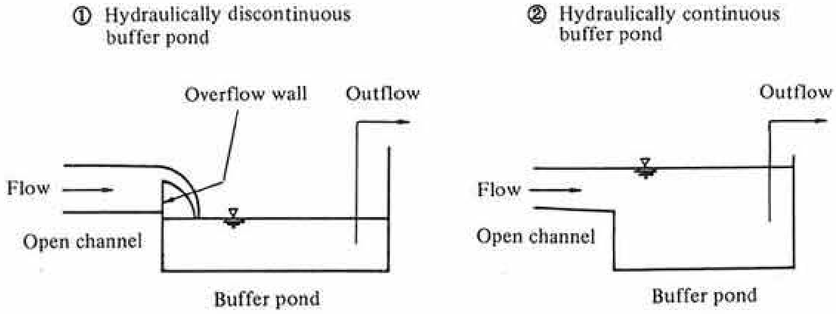

Fig. 1. Inlet of a buffer pond

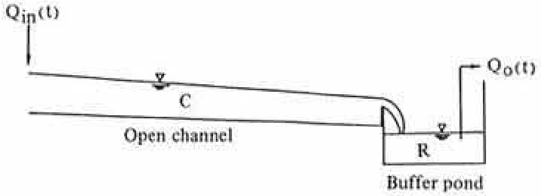

Fig. 2. Schematic explanation of the equation (1)

$Q_{in}(t)$: function of inflow discharge to system (m^3/sec); and

$Q_o(t)$: function of outflow discharge from system (m^3/sec).

The following equation (2) is obtained by integrating the equation (1) as mentioned above:

$$R_0 - R_1 = C_1 - C_0 + \int_{t_0}^{t_1} (Q_o(t) - Q_{in}(t))dt, \quad \cdots\cdots (2)$$

where R_0, R_1 : storage volume of buffer pond at time of t_0 and t_1(m^3); and the maximum value of $R_0 - R_1$ is a necessary capacity of buffer pond.

If in the third term of the right member, $Q_o(t) = Q_{in}(t)$ at both times of $t_0 = T_1$ and $t_1 = T_2$, and beyond T_2 the relation of $Q_o(t) = Q_{in}(t)$ is valid continuously, the following equation (3) is established (Fig. 3):

$$\int_{t_0}^{t_1} (Q_o(t) - Q_{in}(t))dt = \int_{T_1}^{T_2} (Q_o(t) - Q_{in}(t))dt. \quad \cdots\cdots (3)$$

If this value is constant, the fluctuation of storage volume of buffer pond becomes maximum when the value of $C_1 - C_0$ becomes maximum. Therefore, the needed capacity of buffer pond should correspond to such a maximum volume of the storage fluctuation.

Taking into account that the storage capacity (C) of open canal at time t is continuously changing, it should be analysed using an unsteady flow simulation.

Here in the relevant section of a canal, the

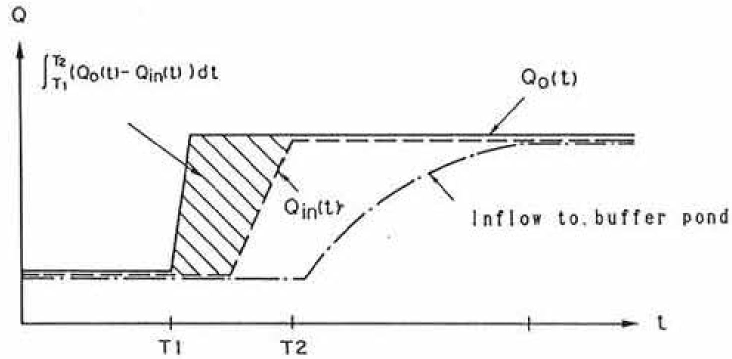

Fig. 3. Schematic explanation of the equation (2)

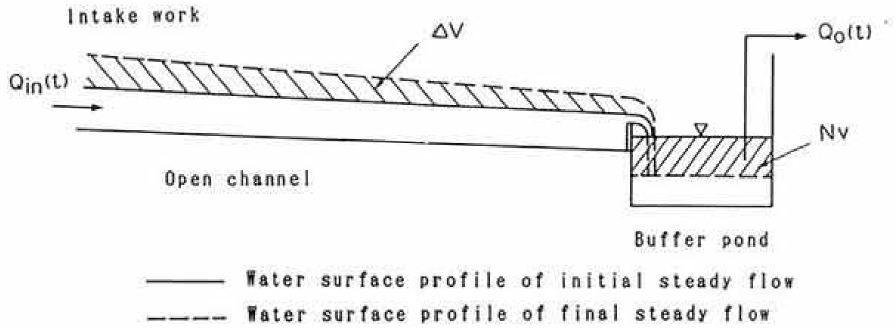

Fig. 4. Schematic explanation of the equation (3)

following assumptions are made: (a) the flows at the time of beginning as well as of changing discharge are taken for non-uniform flow; and (b) the difference between these two flows is taken for the maximum volume of fluctuations of storage. Under these assumptions, the needed capacity of the storage facility, which should be equal to the difference of storage volume in a non-uniform flow canal, is calculated: in other words, the following equation (4) can be obtained (Fig. 4):

$$N_V = \Delta V + \int_{T_1}^{T_2} (Q_o(t) - Q_{in}(t))dt, \quad \ldots\ldots\ldots\ldots (4)$$

where N_V : fluctuation of storage volume of buffer pond between the initial and final volumes (m^3) (= required buffer capacity (m^3));

ΔV : difference of storage volume between the initial and final storage volumes, which is obtained by a non-uniform flow calculation (m^3);

T_1 : the time when $Q_o(t)$, i.e. outflow discharge from buffer pond, begins to change; and

T_2 : the time when $Q_o(t)$ is equal to $Q_{in}(t)$.

The first term of right member in the equation (4) is an outflow volume from buffer pond before water arrival, and the second term is an outflow volume during the delay time of operation of facilities.

Supposing irrigation systems without a buffer pond, the following equation is obtained:

$$C_0 = C_1 + (Q_o(t) - Q_{in}(t))dt. \quad \ldots\ldots\ldots\ldots\ldots\ldots (5)$$

This implies that in changing discharges of water, if the canal has sufficient capacity to store the total volume of the final storage of canal and the outflow volume during the delay time of operation, no buffer pond is required[2)].

2) Verification of calculation equations for buffer pond

In order to verify the equation (4) above, an unsteady flow simulation model is adopted because in establishing the equation, two assumptions are made: i.e. (a) the flow is non-uniform before and after the change of discharge; and (b) the storage volume of canal should be maximum[3)]. A comparative analysis is made between the required buffer capacity (A) obtained by the equation (4) and the change of storage volume of buffer pond (B) obtained on the basis of an unsteady flow model. The model used consists of canals containing upstream-level-constant check-gates, syphons, diversion works and culverts, where the flow is pressurized at the time of discharging estimated maximum volume on the way through horse-shoe shape model tunnels. (Refer to Table 1, length 5.6 km to 20.9 km, longitudinal slope 1/8,000 to 1/1,000[3)]). The result obtained indicates that the difference of ratio $|B-A|/B$ is less than 1% on the whole except for the canal containing check-gates. Therefore, the required capacity of buffer pond in a canal system is calculated, adopting the equation (4) above in practical use, except for the case where the canal system contains check-gates.

Regarding the irrigation system with check-gates, those gates have an insensitive range to water level. Consequently, the difference in the two above, i.e. (A) and (B), becomes large because the water surface

Table 1. Characteristics of open canal models

Model	Cross section	Length	Canal width[a] (Radius)	Longitudinal slope	Steady flow water depth[b]	Remarks
		km	m		m	
I	Rectangle	10.2	2.5	1/2,000	1.677	
II	,,	10.2	2.5	1/4,000	2.207	
III	,,	20.4	2.5	1/2,000	1.677	
IV	,,	20.4	2.5	1/4,000	2.207	
V	,,	5.6	2.5	1/1,000	1.286	Containing a syphon of 0.5
VI	,,	20.9	2.5	1/8,000	2.932	km in open canal system
VII	Horse-shape tunnel	10.2	1.2	1/2,000	1.911	
VIII	,,	20.4	1.35	1/4,000	2.232	
IX	Rectangle	10.0	2.5	1/2,000	1.677	Containing a box culvert
X	,,	10.0	2.5	1/4,000	2.207	of 2.0 km
XI	,,	20.0	2.5	1/2,000	1.677	Containing a box culvert
XII	,,	20.0	2.5	1/4,000	2.207	of 4.0 km

a): For models I to VI and models IX to XII; Canal width; and for models VII and VIII; Radius.
b): Steady flow water depth based on Manning's formula for the case of velocity of 5 m^3/sec.
Source: Reference 3).

contour is continuously changing and the changing storage volume in the canal would reach maximum not at the check level but at the highest water level or at the lowest water level of the insensitive range.

3) Calculation as an example of required buffer capacities using the proposed equation

An example is presented hereafter to estimate a required capacity of a buffer pond in an open canal which is comparatively long and gentle in Japan (length: 20 km, longitudinal slope: 1/4,000)[3]. In order that the outflow discharge from the buffer pond can immediately correspond to the drastic change of discharge from 0 to 5 m^3/sec, which is the estimated maximum discharge, the first term of the right member of equation (4) is equal to about 5 hours' volume. If the time delay of operation of facilities is of 2 hours, the buffer pond needs about 7 hours' volume. In order to make use of water resources effective, we should build a buffer pond of this size at least.

4) Advantages and disadvantages of enhancing buffer function

There are two methods to enhance buffer function: one is to set up water-level regulating facilities and increase buffer function by enlarging the cross section to supply water as required; and the other is to construct a buffer pond as a storage facility.

A study was undertaken to examine advantages and disadvantages of strengthening buffer function for three different cases of open canal model (length 10 km, longitudinal slopes 1/1,000, 1/2,000 and 1/4,000)[3]. The canal adopted by that study had a width one-and-a-half times as large as the water depth of uniform flow at the time of design flow rate (5.0 m^3/sec).

In calculating needed buffer function, a necessary condition is that water depth of 1.0 m can be maintained at the end of the canal when the discharge of 5.0 m^3/sec starts, so that the increase in water demand of 5.0 m^3/sec could be properly dealt with at the end of the canal where the discharge should be 0. In that study, methods for enhancing buffer function presume the following designs:

(1) Raise the height of a canal side-wall, but keep the same width.
(2) Widen the canal in the 2.0 km-distance at its end so that the highest water depth may be 3.0 m at the end of the canal.
(3) Install a buffer pond which directly connects the open canal, and its maximum water depth is 3.0 m.
(4) Install a buffer pond with an overflow wall of 3.0 m height between the canals, and its maximum water depth is 3.0 m.

The results of the calculation based on the aforementioned equations (4) and (5) are shown in Table 2. In case of raising a side-wall to have a buffer

Table 2. Proposed methods for enhancing buffer function

Method	Longitudinal slope		
	1/1,000	1/2,000	1/4,000
1. Raising canal side-wall at the down-stream end	Raising 5.08 m for a steady flow depth (SFD) of 1,469 m, whereby a water depth (WD) of 6,547 m is maintained[a)]	Raising 3.11 m for an SFD of 1,676 m, whereby a WD of 4,786 m is maintained[a)]	Raising 1.70 m for an SFD of 1,872 m, whereby a WD of 3,570 m is maintained[a)]
2. Widening canal width at the down-stream end[b)]	Widening width (WW) from 2.2 m to 13.2 m: Increased canal area (ICA) = 22,000 m^2	WW from 2.5 m to 10.8 m: ICA = 16,200 m^2	WW from 2.9 m to 6.1 m: ICA = 6,400 m^2
3. Buffer pond without overflow wall	Water area of buffer pond (WABP) = 19,649 m^2 (capacity = 39,298 m^3)	WABP = 17,635 m^2 (cap. = 48,689 m^3)	WABP = 8,265 m^2 (cap. = 16,530 m^3)
4. Buffer pond with overflow wall	WABP = 22,934 m^2 (cap. = 45,868 m^3)	WABP = 24,345 m^2 (cap. = 48,689 m^3)	WABP = 21,549 m^2 (cap. = 43,188 m^3)

a): Indicating a water depth maintained when water supply is suspended.
b): The canal is originally designed only for water supply.

function, the wall hight needs to be raised considerably since the longitudinal slope of canal bed is different. Therefore, this method could not be usually adopted, since in most cases, there are great variations in topographical conditions and the water level must be raised.

In case of installing a buffer pond with an overflow weir, the buffer capacity needs larger size, compared with a buffer pond without a weir.

Since the physical works for widening the end portion and installing a buffer pond are similar each other in terms of structure and required area, the buffer function should be designed taking into consideration the related socio-economic as well as topographical conditions.

5) Buffer capacity in a canal system with check-gates

Primarily, a check-gate is installed for the purpose mainly of ensuring water distribution in a canal system. It also has a secondary function incidentally: i.e. when a flow rate in a canal changes, fluctuations of water stored in the system are reduced as compared with the case without a check-gate.

In addition, it is recognized that when the check-gate is provided, there is a greater difference between the fluctuation of buffer pond storage obtained from an unsteady flow simulation and the required buffer capacity estimated on the basis of a check level calculated from the capacity equation.

Buffer capacities necessary for various types of an open canal model installed with check-gates were estimated[3)]. The model consists of 23 different types: i.e. 4 types in length from 5 km to 40 km; 4 types in longitudinal slopes from 1/1,000 to 1/8,000; and 2 types in design flow rates 5 m^3/sec and 10 m^3/sec. It is assumed that all these canals have a rectangular cross section.

Flow rate fluctuations are obtained by two means: one is to shift a flow rate from 0 to design flow rate, and the other is from 50% of flow rate to 100%. Number of installed check-gates ranged from 2 to 13, depending on the specification of the canal.

The results of the study indicate that a required buffer pond capacity could be estimated on the basis of fluctuations of water storage in the canal. Data on those fluctuations are obtained from two measurements: i.e. the lowest check level as the initial water surface at an increase in flow rate and the highest check level as the final water surface. In addition, the check-gate installed has an effect on a buffer pond capacity. An example is presented in Fig. 5, showing the effect of changing of a flow rate from 0 m^3/sec to a designed flow rate of 5 m^3/sec. It indicates that a greater buffer function of the canal could be achieved with a provision of check-gates, and that its effectiveness could be raised by a gentle longitudinal slope of the canal. This result suggests

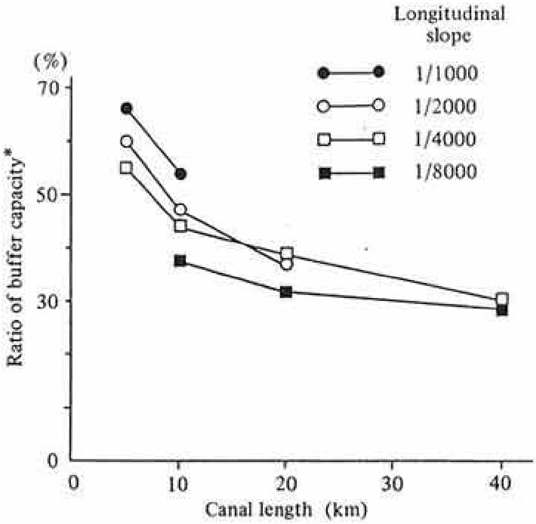

Fig. 5. Reduction ratio of buffer capacity
* Indicating ratios of buffer capacity of canal with a check-gate against that without a check-gate.

that the capacity of the buffer pond can be reduced to the level of 70% saving, depending on the longitudinal slope of the canal.

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